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Reflectors and Night Visibility

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REFLECTORS AND NIGHT VISIBILITY

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HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
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AN ACRYLIC REFLECTING MATERIAL WHICH OFFERS NEW AND UNIQUE APPLICATIONS FOR TRAFFIC SIGNS

R. F. Hibbert, Vice-President,
Reflexite Corporation, New Canaan, Connecticut

Molded acrylic lens sheet is a retro-reflecting product which has many effective applications for traffic signs and signals and for automotive signs and signals as used on cars, trucks and trailers.

This acrylic plastic, sometimes known as Methacrylate, has been in good service and continuous exposure for over ten years.

Acrylic lens reflector sheet is made up of minute spherical lens sections which are an integral part of it. The lenses are arranged in honeycomb patterns and are correctly spaced to provide 2900 accurately molded lens sections per square inch of surface. The smooth back surface of the reflecting sheet is in the focal plane of the front surface lenses and only the area of greatest retro-reflecting efficiency is used in each lens section.

A reflecting medium, usually aluminum flake in a vehicle of acrylic lacquer is applied to the back surface of the sheet. The reflecting system then consists of a multiplicity of minute spherical lenses on the front surface and a reflecting material on the back surface. The lenses, acting in unison, give the whole reflecting pattern an even, bright appearance, when illuminated and viewed from a normal distance.

If a highly concentrated beam of light is desired for long range, narrow divergence is achieved by precise molding to the focal length of the lens, a thickness of .070 in.; conversely, if wide divergence is desired, the plastic is molded off-focus to provide a reflector of lower intensity with a wider divergence angle at a nominal molding thickness of .055 in.

Preliminary research and experimentation proved that an integral lens sheet could be molded and a 1/2 in. square die was eventually made up. Pieces were molded and a sign was fabricated which presented sufficient retro-reflecting efficiency to justify additional research and development.

Acrylic lens sheet offers a fully reflectorized letter stroke and reflected copy may be read at distances at which the eye will resolve copy of the same size in daylight. Halation does not present a problem and an adequate target is provided beyond reading distance.

Acrylic lens sheet also permits a combination of colors arranged in suitable designs or patterns in a single sheet by varying the color of the reflecting material placed on the back of the sheet. Silver reflected letters may be combined with low-reflecting background colors to provide a colorful sign by day and a high contrasting reflecting sign at night.

Additional effects can be had by the use of light-fast dyes backed by aluminum flake combined with dye lacquer, offering a sign of acrylic lens sheet which has daytime aspect at night in legibility, color and shape.

A light reflecting red with light-fast characteristics was developed through research efforts carried on in conjunction with the automobile industry. This light-fast red is obtained with acrylic plastic in combination with red dye lacquer by means of a high-vacuum metallizing technique. This technique is offered to the highway field for useful purposes such as a STOP sign with silver copy and red background, both reflecting.

For general sign production, the reflectorized plastic or acrylic sheet is mounted on metal, plywood, or other backing material with an adhesive. Exposure tests now in their fifth year indicate the efficiency of this method.

These tests also indicate that neither the adhesive, the plastic, nor the acrylic paint will support fungus or mildew growth. Low maintenance cost is assured through the use of acrylic lens sheet, thus justifying a somewhat higher initial material cost.

Individual letter panels available in various fonts and sizes, mounted in flanged aluminum holders offer a convenient method of construction. Such letters can be quickly salvaged for reuse when a sign is damaged or when the background requires refinishing.

Letters may be cut from aluminum-backed reflectorized sheets with a band or jig-saw and fastened to a mounting board either mechanically or by means of an adhesive.

Acrylic lens sheet performs well under stormy weather conditions and snow does not tend to cling to the surface.

The lens pattern breaks up undesirable front surface glare and in locations subject to road film and industrial smoke, the lens may be cleaned with water and detergent. Acrylic lens sheets are durable and not easily damaged by vandals. Localized hair-cracking at the point of impact of sticks, stones etc. does not affect reflecting qualities provided that the cracking does not progress.

AUTOMOBILE GLARE AND HIGHWAY VISIBILITY MEASUREMENTS

Evan P. Bone, Research Engineer
Corps of Engineers, Department of the Army

SYNOPSIS

The results of the measurements indicate that headlight glare is more of a hindrance to full highway visibility than heretofore recognized. Even if the opposing headlights are dimmed to relieve completely the discomfort of glare, the meeting visibility still can be too sluggish for safe travel. Because of the changeableness of eye sensitivity this inadequacy of meeting visibility can escape detection unless there is a standard of measure.

The measurements of visibility here reported, are based on the premise that the driver needs to see as well when meeting other cars as when driving alone in the open road. For economy of electricity the open road visibility provided by present "upper" beam headlights is not more than found, by experience, to be needed. The tests seek to show how dim the opposing glare must be in order to maintain meeting visibility equivalent to the open road visibility.

Considering how the eyes function, we know that when driving in open road the eyes become adapted to the general brightness level of the roadway ahead as illuminated by the headlights and visibility may be reasonably satisfactory and safe. It is possible to maintain the same order of visibility when cars meet, provided the adaptation level from the glare of the other cars is in the same order of brightness as that from the headlighted roadway when in the clear. The procedure of the tests was to measure separately the adaptation level of the eyes when exposed to the roadway illuminated by Sealed Beam (up beam) headlights and then when exposed to the glare of various candle powers. Thus a candle power value of the glare source was found which causes the same adaptation level as does the headlighted roadway. Computations from these test data indicate that meeting visibility up to 80 percent of open road visibility can be attained if the opposing glare is not more than 20 candle power. By comparison, the glare from present headlights may reach 800 to 1,000 candle power even with the beams tilted down.

If such quantitative measure of the effect of glare on visibility is made available, there may be more encouragement for research toward safe headlighting. Then any possible development of superior merit, even if a complete departure from present conventions and concepts, could have a better chance of recognition.

Highway visibility has much to do with highway safety. If the driver can't see conditions on the road ahead he certainly can not be expected to drive safely. Studies of statistics seem to show that the worst driving hazard of all, per mile of travel, is on the rural highways at night. It appears that, on the average, if one drives over a given stretch of highway at night his chances of being involved in a fatal accident are three times greater than on the same stretch of highway in the daytime. What can make such a large difference between night travel and day travel? One sure difference is visibility and in the country we usually are dependent solely upon headlights. It seems apparent that the foremost hindrance to seeing by the use of headlights is glare from the headlights.

We read articles in the papers in behalf of safety which seem to blame accidents on habits of drivers and pedestrians; and to highway alignments and constructions; but little seems to be said as to any mechanical faults of the automobile itself. Certainly, the major cause of the preponderance of night fatalities can be due to the shortcomings of the headlights on the automobiles.

Would it not be worth-while to try some research from a different point of view? For instance, the kind of research which tries first to find what the eye actually needs for highway seeing and then try to design headlighting to suit; - not the other way around. In any basic research it is customary to make measurements Yet in headlighting there appears no direct measure of the effect of glare on highway visibility of the full field ahead. Previous data have been based on measurements of visibility distances of a single target at a particular location along the roadside. But the seeing of a single object is only one element of full field visibility. To take in the full scope of conditions ahead, in the limited time while the car speeds along, the eyes of the driver must resort to the less distinct parafoveal vision and to Gestalt conceptions. This kind of seeing is different from looking at one single object where we have the clear visual acuity of central foveal vision. In the measurements reported herein, an approach is attempted which includes visibility of the full field. When such measurements are made they seem to show the utter hopelessness of the underlying principles of projection as used in present headlighting.

CONCEPTS BASED ON PRESENT HEADLAMP PERFORMANCE NOT APPLICABLE FOR APPRAISAL OF NEW DEVELOPMENTS

If it once is demonstrated and conceded that there is little chance that present headlighting principles can ever accomplish safe night visibility, then the obvious approach would be to open our minds and turn to some other optical principle such as polarizing the light or still other scientific phenomena. But the trouble is that the introduction of any new headlighting development is different from the customary procedure of building up the use of a new product from small beginnings. Any new headlight beam may involve other users of the highways. So it must be a cooperative affair depending upon some central authority representing the interests of all the people. Central authority leads to mass thought and in the absence of a rational measure, general habits of thinking have become so reconciled to present glare and so devoted to previous headlamp performance that any complete departure from established ideas and precedents is expected to meet resistance. Experiences indicate that this situation does exist and has tended to retard research.

Of course uniform standards and rules are necessary for interpreting the State statutes for regulating present headlamp practice. Current problems must be met year by year, and it is understandable why the beam specifications have been drafted to include existing headlamp performance.

But basic research is another problem. These rules or orthodox concepts and thinking in terms of these rules are not applicable for sizing up new developments. Certainly innovations should be gaged on measurements of what the eye is capable of doing, regardless of what previous headlamps have been doing. However, because the rules for previous headlamps have had to ignore the effect which glare has on visibility, it does seem that of the two major causes which have been considered for universal adoption - the Sealed Beam and Polaroid - the full advantages of reducing glare to a minimum were ignored. In each of these improvements better driver visibility could have been secured if consideration had been given to the quantitative effects of disability glare. What chance does any invention or new development have if the real hindrance to night visibility - glare - is not to be given full consideration in balancing the advantages against the disadvantages?

There is hope that if means for isolating and quantitatively measuring the effects of glare are made available, decisions can then be based on factual data rather than upon opinions. It is the purpose of this paper to report a method for quantitatively measuring disability glare.

MEASUREMENT OF DIFFERENTIAL BETWEEN MEETING VISIBILITY AND OPEN ROAD VISIBILITY

The measurements of visibility in the present study are based on the premise that the driver needs to see as well when meeting other cars as when driving alone in open road. The needs for headlight beam patterns for adequately viewing the full scope of the field ahead when driving alone in open road have already been worked out as now accomplished in the modern Sealed Beam "uppers". Further increase in volume of light could be secured at any time, with no change in the basic optics of projection, merely by the use of larger parts and the expenditure of more wattage. So we are concerned only with the difference between visibility against glare and open road visibility; and the starting point, or datum, from which the effects of glare are reckoned in this study is taken as the open road visibility from present headlighting. The measurements submitted herein are to show to what extent glare needs to be reduced in order to obtain meeting visibility which approaches present open road visibility.

The results of measurements to date, as reported in detail below, indicate that to get meeting visibility up to, say 80 percent of open road visibility, the opposing glare must be restricted to at least 20 c.p. with the driver's own headlights still giving him the same field brightness as do present Sealed Beam "uppers". This is a ratio of over 2500 to 1 between the candle powers of the beam for long ranges and the glare.

By way of comparison, the meeting beams of present headlamps may give 800 to 1000 c.p. glare and are so tilted that their main force strikes the foreground only some 100 or 200 ft. ahead. Visibility straight ahead for reasonable driving ranges is extinct.

DISCOMFORT GLARE AND DISABILITY GLARE

A factor which perhaps may need some clarification in this study, is the difference between discomfort glare and disability glare. As a hypothetical example let us suppose we are approaching another car with headlights shining say 10,000 c.p. glare in our eyes. We feel that this glare is uncomfortable and irritating. Then if the beams of the other car are shifted down to, say, 1,000 c.p. it seems like a welcome relief. The glare seems gone. However that reduction of 10 to 1 is a small part of the ratio of over 2,500 to 1 needed for visibility. This example may illustrate why when glare is reduced only on the basis of easing the eyes of opposing drivers it may be nothing more than a feeble gesture toward maintenance of adequate visibility.

EFFECTS OF CHANGES IN EYE SENSITIVITY - ILLUSTRATIVE EXAMPLES

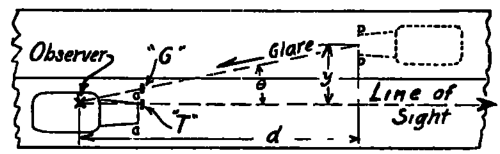
In considering the results of the measurements it may be kept in mind that the depletion of visibility in the presence of glare is solely a question of change in eye sensitivity. What really is measured, although objectively, is eye sensitivity. It is almost beyond our comprehension just how much eye sensitivity does change. As an example, the level of illumination in sunlight may be one billion times greater than under starlight. Yet our eyes so change that we can see to get around in both cases. At any one setting, or adaptation brightness level of the eye, within that extremely wide range, the band within which the eye normally can function - pure white against dead black - is only a contrast of 100 to 1; - quite a small fraction of a billion times. As another example, the stars in the sky are sending as much light down to us in the daytime as at night but we do not see them by day. The change is not in the stars. It is in our eyes.

NORMAL SEEING AND PRESENT AUTOMOTIVE SEEING

These are examples of a phenomenal property of the eyes. That is, the changeable sensitivity of the eye somehow maintains a fixed relationship to the surrounding brightness to which our eyes, for the moment are exposed. Let us first examine how normal seeing works and then how and why the customary combination of headlight illumination and glare fails to work.

In normal seeing when the candle power of the source of illumination is increased, the brightness of all objects within the field, and their brightness differences, increase in direct proportion. Under these increased brightnesses, the eye does not need to be as sensitive for maintenance of the needed seeing ability. So nature has provided that when the general brightness of the field increases in this manner the eye sensitivity decreases. The decrease is in almost straight line inverse proportion to the brightness. One change offsets the other and visibility remains about the same. This wonder of nature, and it is a wonder, acts in accordance with Weber's law of psychophysics which, when applied to the sense of sight, can be stated as: "the least perceptible brightness difference is a constant fraction of the surrounding brightness." The "least perceptible brightness difference" is a measure (inverse measure) of eye sensitivity.

FIG 1



Test Car - Plan

Present headlighting habits are contrary to this law of nature. When driving in open road, our eyes become adapted to the brightness of the field illuminated by our headlights, most dominant of which is the pavement surface in the foreground, and visibility may be reasonably satisfactory and safe. When meeting another car having present style headlights, things drastically change. The effective brightness of the opposing glare, even with the lower beams, is so much greater than the road brightness to which our eyes have been adapted that, in accordance with Weber's law, the optical sensitivity of our eyes drops way down. Now, in normal seeing, eye sensitivity goes down only when the field brightness has gone up. In this instance, however, the brightness of objects in the field ahead, as illuminated by our own headlights, has not increased to compensate for the drop in eye sensitivity from the glare. In fact it is required that drivers tilt down their beams and take light away from the long ranges, instead of increasing it. This is not normal seeing, it is contrary to natural laws and visibility becomes extinct at the longer ranges.

The effect is that just at the critical time whenever cars meet and pass each other, both drivers must blindly enter head-on into a zone of darkness. Even at modest speeds, both are temporarily incapacitated and many things may happen such as colliding with each other, running off the road, running down a pedestrian, or suddenly encountering an unexpected obstruction. This situation is the crux of the night highway visibility problem.

MEASUREMENTS - EQUATING GLARE BRIGHTNESS TO OPEN ROAD FIELD BRIGHTNESS

In considering the above mentioned characteristics of the eye it is obvious that it would be possible to get meeting visibility to approach open road visibility if, without changing the illumination on the road ahead, we keep the opposing glare down to the same order of brightness as the field brightness illuminated by our headlights; - that is, if we keep eye sensitivity near the same both when meeting and when alone in open road. The procedure in making the measurements is to find, in terms of candle power, what brightness of opposing glare is equal to the brightness of the headlighted field.

TEST EQUIPMENT

The simple apparatus used for making such measurements is installed on a test car as illustrated in Figure 1. This is a plan view of a portion of a highway with our test car shown in full lines and a possible glare car in the adjacent lane shown dotted. In addition to standard Sealed Beam glass reflector headlamps, the test car is equipped with two sources of brightness, "T" and "G". The brightness source "T" is in the shape of a 1-deg. square target framed by a 1/2-deg. black border. The target is in the driver's line of sight when looking toward the most distant objects on the highway directly ahead. The brightness source "G" is a small incandescent lamp, such as used in taillights and is in direct line between the driver's eyes and the position of opposing headlights in the adjacent lane at a distance where glare may be bothersome - say 100 ft. Thus, the small lamp "G" has the same effect on the driver's eyes as opposing glare, the actual candle power values being adjusted, of course, in accordance with the inverse square of the distances from the eye to the sources. The brightnesses of each of these sources "T" and "G" are independently controlled by rheostats in their respective electrical circuits. A special voltage regulator is used for obtaining brightness consistency in all tests.

The target "T" is the yard stick for the measurements. That is, a balance is found in which some setting of the brightness of target "T" is just barely visible when the driver's eyes are exposed solely to the field illuminated by his own headlights and also is just barely visible with his eyes exposed solely to some certain candle power value of glare "G". With this balance, the effective sensitivity of the eye must be the same when exposed to that particular candle power glare as when exposed to the headlighted highway. Also, the "contrast sensitivity" is the same in both cases. This gives a unit for evaluating the glare in terms of open road visibility.

TEST PROCEDURE

The observations for just barely visible brightness between target "T" and its dark background were made in two phases. In one phase the eyes of the observer were exposed to the glare lamp "G" alone, and in the other phase to a headlighted roadway alone. The observations were made in runs, each run being made with a fixed candle power value of glare lamp "G" ranging from the equivalent of 25 to 800 c.p. glare in the one phase and at a given highway location in the other phase. From 50 to 283 separate observations were taken in each run. The collected data from the respective runs were plotted and the curves for the two phases matched graphically for finding the balances between adaptation levels from exposure to glare and exposure to the headlighted roadway.

The observations with eyes exposed

to the glare "G" could be done in an undisturbed yard so that only the observations from the headlighted roadway had to be made on the public highways.

The black border of target "T" was of such low brightness during all tests, that the "minimum perceptible brightness difference" between target "T" and its background was equal to the "minimum perceptible brightness" of the target itself. Care was used to keep factors, other than brightness, constant; - such as, size of target, orientation of the line of sight and time of exposure. The 1-deg. size of target was selected as most typical of major objects to be seen on highways. The line of sight was always directed straight ahead toward the horizon during both phases of the tests. As to exposure time; - just before each run, the eyes of the observer were exposed to the specific brightness of the glare lamp "G" or to the headlighted roadway, as the case might be, for a sufficient period for long time adaptation. Starting at an unknown position of the dial which regulates the brightness of target "T", it was gradually increased at a uniform rate until just visible. This was done manually after preliminary practice. Each observation was made by ascending rather than descending brightness of the target "T" in order not to molest the adaptation level of the eye by the brightness of the target itself.

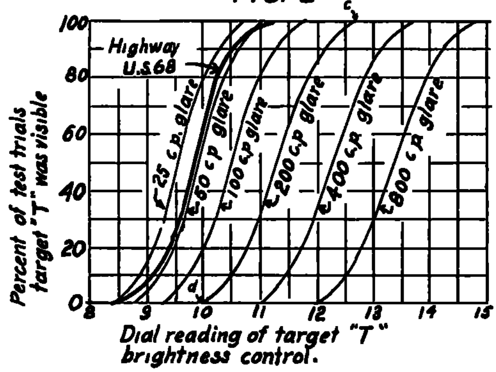
It is to be noted that the brightness of the target, as to itself, has no significance. It is only that whatever visual arrangement of the target might be selected for the tests it must be the same when exposed to the headlighted roadway as when exposed to the glare. The sole function of the target was to strike a balance for equality of the seeing capability with eyes exposed to the headlighted roadway as when exposed to the glare.

It is not intended that the particular results here reported are final. A more elaborate program could procure more refined and reliable data. However, it is believed that the present measurements give adequate data for quantitatively demonstrating the serious discrepancy in current concepts of the effect of glare on highway visibility.

TEST RESULTS

The summarized test data are shown in Figure 2. The light line curves are from tests of the visibility of target "T" against various candle power glares. The heavy line curve gives the visibility of target "T" with eyes exposed to the highway illuminated by the headlights. The readings for this particular curve were taken on highway U. S. 68, one mile north of Midland, Ohio. The horizontal scale is a function of the brightness of target "T".

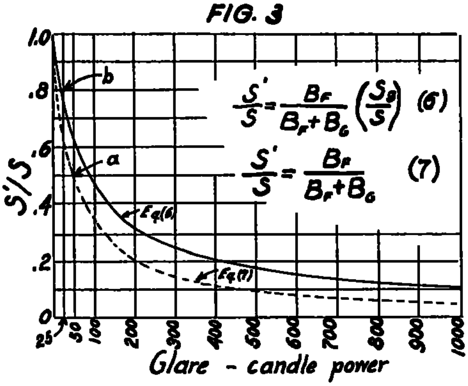
FIG. 2



It is in terms of the dial settings of the rheostat which governs the brightness of target "T". (For the purpose of comparison it is not necessary to reduce the dial readings to units of brightness but they were in the order of 0.0003 foot lambert.) The vertical scale gives the percentile or percentage of total test trials of each run in which target "T" was visible. For example, in the test when facing 200-c. p. glare, target "T" was visible at all settings of the dial above 12.6 indicated at c, and at no settings of the dial below 10.0 indicated at d.

The plan at first was to collect visibility data for different types of highway pavement, roadside development, etc., but it did not work out that way. The deviations of the visual perceptions under identical conditions were much greater than deviations at different highway locations. For instance, the test run plotted by the heavy line curve of Figure 2 coincided almost precisely with runs taken on other highways. There were indications, however, that some locations on sparsely used highways gave higher adaptation brightnesses but on well aged and traveled highways where rigid pavements had become darker, and flexible pavements lighter, no material difference in brightness could be detected. So these observations on highway U. S. 68 were taken as typical.

FIG. 3

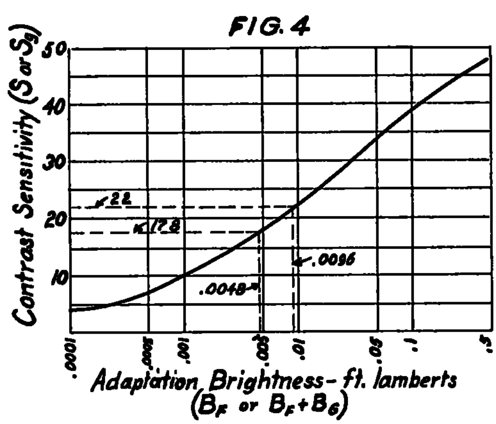


It is noted in the curves of Figure 2 that the average adaptation brightness of the eye exposed to this headlighted highway (heavy line curve) approximately matched the curve for 50 c.p. glare. Interpolation between the 25 c.p. and 50 c.p. glare curves might indicate nearer coincidence but considering other uncertainties in measurements of this kind, 50 c.p. is a sufficiently close approximation. This is the information sought from the tests. "Eye sensitivity" or "adaptation brightness level" is the same when facing 50 c.p. glare on a straight two-lane highway as when facing the headlighted field.

COMPUTATIONS OF MEETING VISIBILITY IN TERMS OF OPEN ROAD VISIBILITY - BASED ON MEASUREMENTS

The result of the measurements means that eye sensitivity is practically the same when facing 50 c.p. glare alone and when viewing the headlighted highway alone; - either one or the other. Actually in the situation of meeting another car, the driver's eyes are exposed to both the glare and the headlighted roadway. This is accounted for in the complete study of the actual meeting conditions as summarized by the curves and equations of Figure 3. The derivations of Equations (6) and (7) which are based on the Holladay (1)[1], (2) analysis of glare are given in the

FIG. 4



Appendix.

It may be recalled that the findings and analysis by L. L. Holladay of the Nela Park Laboratories of the General Electric Company were presented in a number of technical papers back in the 1920's. As now included in the recently published Illuminating Engineering Society Lighting Handbook, the analysis seems to be applied mostly to problems of interior lighting. But of all places where glare needs to be analyzed, it is automobile glare.

In Equations (6) and (7) the symbol S represents "Contrast Sensitivity" when in open road and S' is the "Effective Contrast Sensitivity" when meeting glare. The technical term "contrast sensitivity" may be considered as a general measure of visibility under any particular lighting condition, and general "visibility" as used herein is synonymous with "contrast sensitivity". The meaning of "contrast sensitivity" is, of course, different from the more

[1]See references listed at the end of this paper.

generic connotation referring to sensitivity of an instrument or human sense organ as we have been saying in respect to general eye sensitivity. In the equations, the symbol S can be considered to represent open road visibility and S' to represent meeting visibility. So the fraction S'/S gives the ratio of meeting visibility to open road visibility. The symbol B_F is the adaptation brightness level of the eye from the field as illuminated by our own headlights and B_G is the adaptation level from the opposing glare source. Equation (7) is in more general terms and assumes Weber's law to hold rigorously. Equation (6) is nearer exact in that variations in Weber's law at the relatively low illumination levels encountered in headlighting are accounted for as discussed in the Appendix.

It is noted in Equation (7) for example, that if B_G is large compared to B_F, S'/S is small and meeting visibility is low. This is the case with present headlights. To get meeting visibility which really approaches open road visibility, B_G needs to be small. The condition which was measured in our test was when $B_F = B_G$, in which case the fraction S'/S is equal to 0.5 and meeting visibility would be 50 percent of open road visibility by approximate Equation (7). For this condition the source of glare brightness was measured to be 50 c.p. Starting from this point a of ordinate 0.5 and abscissa 50 where $B_F = B_G$, Equation (7) is plotted as the broken line curve. The glare brightness B_G can be expressed in candle power as shown since the brightness B_G and the candle power I_G of the glare are directly proportioned to each other. (As derived in Appendix $B_G = .0000955\ I_G$.)

The full line curve which is a similar plot of Equation (6) gives nearer exact values of S'/S because variations from Weber's law are accounted for as explained in the Appendix.

CONCLUSION

The conclusion resulting from the tests is shown by the full line curve of Figure 3. If meeting visibility is to be anywhere near equivalent to present open road visibility, say within 80 percent, as indicated by point b on the curve, the glare must be reduced to 20 c.p. Such performance will seem fantastic if we keep thinking in terms of present headlamp performance. However, if the magnitude of the glare effect is once made known and a clearly defined ideal is set up as a goal to strive toward, there may be more incentive for the development of night driving safety measures. The diagnosis of the case might lead to a remedy.

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2. Holladay, L. L., "Glare of Street Lamps and Its Influence on Vision", *Transactions*, Illuminating Engineering Society, Vol. 21, p. 969, 1926.
3. Illuminating Engineering Society Lighting Handbook, pp. 2-20, 1947.

APPENDIX

Equation (7), Figure 3, gives the approximate ratio between general visibility when meeting glare and when in clear road. Equation (6) gives a nearer exact ratio by consideration of variations from Weber's law. The background for the derivation of Equations (6) and (7) is given below by reference to the Holladay (1), (2) analysis of disability glare.

Sensitivity of the eye as used in the present study may be expressed as:

$$\text{Sensitivity of the eye} = \frac{1}{\Delta B} \quad ..(1)$$

where ΔB is the minimum perceptible brightness difference. It is a measurable quantity as determined by finding the borderline (threshold) between when the test target is seen and is not seen.

Contrast Sensitivity, S, is a measure of general visibility and is expressed by:

$$S = \frac{B}{\Delta B}$$

where B is the adaptation brightness corresponding to the momentary mimimum perceptible brightness difference, ΔB.

In accordance with Weber's law S is practically constant at approximately 100 throughout the wide range of brightness levels within which the eye is capable of operating. At the lower brightnesses, the contrast sensitivity S, falls off to unity at the absolute threshold of vision. The change from 100 down to 1 occurs in about $\frac{1}{1000}$ th of one percent of the complete brightness range of vision. It is within this $\frac{1}{1000}$ th percent that headlighting brightnesses are encountered. To account for different values of contract sensitivity, we may designate:

$$S = \frac{B_F}{\Delta B_F} \quad ....(2)$$

and

$$S_g = \frac{B_F + B_G}{\Delta B_{(F+G)}} \quad ....(3)$$

where B_F is the adaptation brightness from the field as illuminated solely by our own headlights and B_G is the adaptation brightness from opposing glare. ΔB_F and $\Delta B_{(F+G)}$ are the minimum perceptible brightness differences for adaptation brightnesses B_F and $(B_F + B_G)$ respectively.

Equation (2) expresses the actual Contrast Sensitivity for normal seeing when driving alone in open road. Equation (3) is a fictitious condition in which the state of normal seeing is assumed when meeting glare. (This does not exist.) That is, when meeting the glare, the effective brightness to which the eyes are exposed increases from B_F to $(B_F + B_G)$. Accordingly, the minimum perceptible brightness difference increases from ΔB_F to $\Delta B_{(F+G)}$, as given in Equation (3). But the field brightness which contributes to visibility remains at B_F as in Equation (2). So the "effective contrast sensitivity", S', when meeting the glare, is fixed by the field brightness B_F, (the same as when in open road) and by the minimum perceptible brightness difference $\Delta B_{(F+G)}$ as when the eyes are exposed to both the glare and the illuminated field, expressed by the formula,

$$S' = \frac{B_F}{\Delta B_{(F+G)}} \qquad \ldots.(4)$$

The ratio between the effective contrast sensitivity when meeting glare and the contrast sensitivity when alone in clear road, is, by dividing Equation (4) by Equation (2).

$$\frac{S'}{S} = \frac{\Delta B_F}{\Delta B_{(F+G)}} \qquad \ldots.(5)$$

But from Equation (2) $\Delta B_F = \frac{B_F}{S}$ (2a)

and from Equation (3)

$$\Delta B_{(F+G)} = \frac{B_F + B_G}{S_g} \qquad \ldots.(3a)$$

Substituting these values of Equation (2a) and Equation (3a) in Equation (5).

$$\frac{S'}{S} = \frac{B_F}{B_F + B_G} \frac{S_g}{S} \qquad \ldots.(6)$$

When Weber's law can be considered to hold rigorously, $S = S_g$ and

$$\frac{S'}{S} = \frac{B_F}{B_F + B_G} \qquad \ldots.(7)$$

This expression gives an approximate ratio between the general visibilities when meeting glare and when in clear road. The measurements of the tests indicate that, when the opposing glare is 50 c.p., $B_F = B_G$ and from Equation (7), $S'/S = ½$. With this point fixed the broken line curve of Figure 3 is plotted for other values of glare brightness, B_G.

For a nearer exact analysis, accounting for variations in Weber's law, it is necessary to find the actual brightness values of B_F and B_G. The Holladay-Stiles formula for adaption brightness caused by glare, as given in the Illuminating Engineering Society Lighting Handbook (3) is:

$$B_G = \frac{10 \pi E}{\theta^2} \text{ foot lamberts.} \qquad (8)$$

where E is the illumination in foot candles in the driver's eyes from the opposing glare and θ is the angle, in degrees, at the driver's eyes between his line of sight straight ahead and the direction toward the opposing headlights. For a straight highway, the angle θ is relatively small and can be considered to be proportional to its tangent

$$\theta = 57.3 \frac{y}{d} \text{ degrees} \qquad \ldots.(9)$$

where y is the lateral distance and d the longitudinal distance between the driver's eyes and the opposing headlights, both in feet. (Fig. 1). Also,

$$E = \frac{I_G}{d^2} \qquad \ldots.(10)$$

where I_G is the opposing glare in candle power. Combining Equations (9) and (10) in Equation (8) the distance, d, cancels out, and

$$B_G = \frac{.00955\ I_G}{y^2} \qquad \ldots.(11)$$

For a typical two-lane highway, y = 10 feet, whence, from Equation (11),

$$B_G = .0000955\ I_G \qquad \ldots.(12)$$

It was found from the measurements, reported herein, that when $B_G = B_F$,

$$I_G = 50 \text{ candle power}$$

Substituting this value of I_G in Equation (12)

$B_G = B_F = .0048$ foot lamberts, and

$$B_G + B_F = .0096 \text{ foot lamberts}$$

Referring to the curve of Figure 4, which is taken from Holladay's data, (Fig. 7, page 969, Illuminating Engineering Society Transactions, 1926) it is found that for B_F = .0048 foot lamberts, S = 17.8 and for $B_F + B_G = .0096$ foot lamberts, $S_g = 22.0$.

Substituting the above values for B_F, B_G, S and S_g in Equation (6)

$$\frac{S'}{S} = \frac{.0048\ (22.0)}{.0096\ (17.8)} = 0.617$$

This is the ratio between "Effective contrast sensitivity" when meeting 50 candle power glare and "Contrast sensitivity" when alone in open road. The ratios when meeting other values of glare as computed from Equation (6) and with reference to the curve of Figure 4, are plotted as the full line curve of Figure 3.

Note: It may be observed that the curve for contrast sensitivity in Figure 4 (which is taken from Holladay's data) is considerably different from the similar curve in I.E.S. Lighting Handbook. As investigated by Holladay, as encountered in automotive seeing and as measured in this study, brightness differences of larger objects (in the order of 1 degree sustended angle) are of more concern than visual acuity of fine detail.

DISCUSSION

DR. A. R. LAUER, *Iowa State College* - In the first place may I say that Mr. Bone has sensed an important problem in driving, although for most drivers it is not a crucial one. A few persons are blinded badly by light and any method which would help them in this respect would be justified and of value.

I seriously question his statement that, "it is possible to maintain the same order of visibility when cars meet." His proof of the statement is decidedly vague. He speaks of glare as being not more than 20 c.p. and again up to 800-1000 c.p. I think his terminology is confused. Candle power refers primarily to the power of the luminaire. The direct light emitted and measured at any given point is designated as foot-candles. It decreases with distance approximately according to the inverse-square law.

Our studies have indicated that the light from two cars meeting rarely exceeds 1.25 f.c. at the eye of the driver. These measurements were made by actual road tests. The candle power of the luminaire remains the same except for the decrease in each direction away from the "hot spot" of the beam. I do not understand his discussion of variable candle power.

The effect of glare is greatly reduced by general illumination of the surroundings. The adaptation of the eye, as Mr. Bone points out, is enormous. Therefore we are inclined to minimize the cogency of his argument of the ill effect of approaching lights and the possibility of neutralizing it. Our studies have shown a proportional decrease in visual acuity with any source of opposing light.

Again he seems confused in speaking of Weber's law of psychophysics and using symbols ordinarily associated with Fechner's law. The two are not the same and it is not clear just which he means to utilize in his theory.

So far as his experiments are concerned they seem to back the precision of controls and statistical evaluation which we would like to see and it is conceivable that his rheostat with consequent changes in wavelength of light would void any conclusions made.

It would be my suggestion that Mr. Bone completely rework the paper, repeat his experiments with more rigid controls and carefully revised his terminology to suit the usage made. Unless written up in such a fashion that one might repeat his study exactly I am afraid its influence and usefulness will be quite limited. In the present form it does not do justice to the effort he has undoubtedly put into it.

R. P. TEELE, *National Bureau of Standards* - Several members of the Committee on Night Visibility do not agree with the findings reported by Mr. Bone. Two members submitted written comments and I have been asked to comment on these and the paper (one of these was withdrawn).

It is certainly conceded by those working in the field of night visibility and by motorists that the present seeing conditions on the roadways at night using existing headlights and street lighting installations are not ideal. If they were ideal we would not have a night visibility committee.

Part of the comments submitted, I believe, are brought about by nomenclature differences. In the paper the words "eye sensitivity" are used where "brightness-contrast sensitivity of the eye" is the more common term. The two expressions are not interchangeable and convey very different meanings.

There are one or two other technical points which are open to question but they would require a long and rather technical discussion and these are being passed over to bring out several things which are considered to have more bearing on the differences between the present results and other experience and tests.

A glare source of 20 candles has been found by Mr. Bone to be the maximum allowable for 80 percent "open road visibility". From experience with observer drivers engaged in headlight tests, it has been found that to obtain 80 percent of clear road visibility distance, we can allow much more than 20 beam candle power from oncoming headlamps. The present sealed-beam headlamps, when the depressed beam is used, have a beam candle power of 800 to 1000 above the horizontal and to the left, that is, toward the approaching car. What causes this factor of 40 to 50 between the test just reported and driver observer experience?

The present work was done "in an undisturbed yard" when the glare source was being used. The glare source was viewed against a comparatively dark background. It is not clear in the paper what comprised the background for the target. However, if I understood Mr. Bone correctly, the headlights were turned off when the glare source was being tested and presumedly the background for the target was also comparatively dark.

When we try to apply this laboratory experiment to actual driving conditions, what factors must be considered?

First, let us consider attention. In the yard laboratory attention is directed at one problem. In driving, a considerable amount of attention should be given to operating the motor vehicle, and the glare source viewed as a side issue with whatever part of our total awareness is not used in driving. This division of attention is not a small factor.

Then there is the time element. How long is the glare source in the field of view? The time is important; if a flashbulb were flashed here we would hardly be aware of it. Certainly our seeing ability would not be appreciably altered. However, if a source of the same candlepower as the peak intensity of the flashbulb were held in the same place, we would be temporarily blinded by it.

Next let us consider the background-to-glare-source contrast. In the yard laboratory a dark background was used.

On the road the headlights of the oncoming car are viewed adjacent to a surface lighted not only by our own headlamps but by the headlamps of the oncoming car. This field brightness influences the adaptive state of the eye. In one case it is quite low and on the road appreciably higher, the actual value depending upon the reflectance of the road surface. There is little doubt that the adaptive state in the yard laboratory was appreciably lower than would be encountered in night driving. The influence of the adaptive state is a common experience. Headlights observed in the daytime or on a well-lighted street are not nearly as glaring as the same lights observed on a rural highway at night.

A point not covered in the paper is the fixation point. If the attention is directed at the glare source and the target viewed by off the axis vision, the situation is quite different from directing the attention at the target and viewing the glare source by off the axis vision. This is easily demonstrated at night by directing the eyes at the right-hand edge of the road when a car is approaching. Approaching lights are much less glaring then than when one looks directly at them. Many motorists fail to make use of this fact when driving at night.

The points just discussed all lead to the obtaining of a higher value of allowable candle power for a glare source in observer driver tests than in the yard laboratory tests just described. The latter are such that a minimum value of the maximum candle power of the glare source is likely to be obtained.

Other experimenters find a large difference between laboratory work and field practice. P. J. Bouma, in a paper in the Philips Technical Review, Vol. 4, January, 1939, found a multiplier of 200 to be correct in applying laboratory visibility observations to practical navigation. In blackout studies during the war, described in a paper by W. S. Everett and Kirk Reid, a factor of 100 was used when observations were made from planes flying at 150 to 200 m. p. h.

It seems likely that in the present case a factor somewhere between 10 and 50 would be found if an extensive series of tests were made under both sets of conditions. The work reported here and values found in observer driver tests are in all probability not as divergent as it seems at first glance.

E. P. BONE, *Closure* - It is regrettable that one of the written comments mentioned by Mr. Teele has been withdrawn and that the other committee members who did not agree with the findings as reported in the paper have not voiced their objections. About one-half of the voting members of the Night Visibility Committee opposed the paper. In response to a number of questions and doubts which have been indicated, I shall try to answer the points raised by the discussions of Mr. Teele and Dr. Lauer in some detail.

It is gratifying to read in the closing two paragraphs of Mr. Teele's welcome discussion why the results reported in the paper and the results from other generally recognized tests "are in all probability not as divergent as it seems at first glance". It is interesting that Mr. Teele points out visibility problems of navigation and airplane flight where laboratory observations are multiplied by factors ranging up into the hundreds for use in actual practice. It has not been customary to use any such large factors for automotive seeing for which Mr. Teele now suggests a factor between 10 and 50. It appears that hereby is the principal point of controversy.

Let us examine why there may be a need for such high factors. In laboratory tests, it is customary to measure the visibility of some single target taken as a standard. However, the adequate seeing of any general field of view depends upon many objects and details and in this respect is entirely different from the seeing of a single test target. There are many reasons for this, one of which is that the complete field of view cannot be comprehended in one look. Normally the eye scans its field fixation point by fixation point. This consumes time, and time is limited when driving an automobile. These phenomena constitute a separate study in themselves but consideration is here invited to such factors because they seem to be the reason for some of the skepticism of the results which I have reported. In observer driver headlight tests as further cited by Mr. Teele it is customary to study the visibility distance of only a single target such as the figure of a man in dark clothing.

In the paper a different approach was attempted in which it may not be necessary to speculate on these wide factors between laboratory test seeing and seeing in actual practice. It may be kept in mind in reviewing the paper that the approach here attempted rests on the simple logic that if we keep the illumination on the field of view the same when meeting cars as when alone on the road, and somehow keep the adaptation level of our eyes near the same in both cases, then our overall visibility must be near the same in both cases.

The glare analysis is based on the findings of L. L. Holladay and his contemporaries. The Holladay data are expressed in several empirical formulas, one of which is listed as Equation (8) in the Appendix. I may have put too much emphasis on my own testing because all I have done was to make a few incidental tests for reducing visibility against glare as treated by Holladay and visibility when alone on the road, to a common denominator. Then by calling visibility when alone on the road 100 percent, we can isolate and evaluate the relative effects of glare. My testing had nothing whatever to do with measuring the visual discernment of any particular objects on the highway. It was only for comparing general visibility when facing oncoming headlight glare with general visibility when alone on the road, whatever the latter may be. The reason for isolating the effects of glare is that better clear road visibility can be obtained merely by increasing the candle power of present headlamp designs. But this would increase glare in proportion. To keep the glare down, some new application of optical principles seems to be needed.

Holladay's findings for quantitatively evaluating glare have been before us for the last twenty-five years. Yet, until very recently, it seems that no use of them has been made for headlighting. When the Holladay formulas are applied to headlight glare they immediately show the hopelessness of attaining safe driving when cars meet each other on the country roads at night by devices based on the optical principles of present type headlamps. But the usefulness of the Holladay analysis goes further than that. It shows what the eye needs for obtaining safe night visibility. Some of us who have been devoted to headlighting from other than, let us say, orthodox viewpoints, have very practical reasons to be convinced that the mechanical and optical means are at hand for a complete reform of headlighting in the cause of night driving safety. The difficulty in enacting such reform is not with headlamp constructions. It seems rather that, in our wishful thinking to condone, somehow, the present lack of night visibility, we let our interests become diverted away from the primary essentials for securing that night visibility. This brings in one of the most difficult problems of all. When thinking of reducing glare we are apt to disregard the extent to which it needs to be reduced unless we are willing to get back to thinking in more fundamental terms of the phenomena of seeing.

Both Mr. Teele and Dr. Lauer refer to "nomenclature" and "terminology" and also bring up a number of questions about the method of testing. It is in the attempt to express some quantitative concept of the magnitude of the changes in the eye, that the more fundamental terms were used in the paper than are considered necessary in most conventional problems of visibility. As to the technique of the tests, the details in general were intended to follow routine practice. However, in view of the questions which have been brought up, both nomenclature and test methods will be discussed in some detail below.

For clarifying any misunderstanding of nomenclature let us consider Mr. Teele's statement, "In the paper the words 'eye sensitivity' are used where 'brightness-contrast sensitivity of the eye' is the more common term. The two expressions are not interchangeable and convey very different meanings". Contrary to Mr. Teele's impression, the meanings of the two terms were intended to be different. The concept of eye sensitivity, expressing the state of being sensitive, was purposely used because it may give a better realization of the quantitative effect of glare. In normal seeing the eye adapts itself to the prevailing brightness and this automatically helps seeing. So an elastic unit of measure, such as contrast sensitivity, which goes up and down with the large changes in general brightness, is adequate and very useful for many problems of visibility. But in automotive night seeing the adaptation action, as dominated by oncoming glare, is a hindrance, rather than an aid, to the seeing. If we are to get anywhere near equivalent visibility when cars meet as when in clear road, the eye sensitivity must be near the same in both cases. That is, so long as the illumination on the road is kept the same in both cases. Or, we could just as well say adaptation level must be near the same in both cases. But when making comparisons with some other condition of seeing such as between the 20 c.p. glare for near ideal visibility and the 800 to 1000 c.p. glare as from present headlights, we should use the term eye sensitivity, not adaptation level. The reason for this is that at low levels of illumination, the ratio between eye sensitivity and adaptation level varies with brightness. The difference is illustrated in Figure 3, where the dotted line curve shows the approximate comparisons when assuming the relationship between adaptation level and eye sensitivity to be constant and the full line curve shows the comparisons when accounting for the actual changes which exist in their relationship.

The difference between the two terms eye sensitivity and contrast sensitivity is specifically defined in the article of the paper headed, "Computation of Meeting Visibility in Terms of Open Road Visibility - Based on Measurements", in the third paragraph. Then in the Appendix they are further defined even in the exactness of mathematical formulas. At the beginning of the Appendix "eye sensitivity" is evaluated by Equation (1). Then in the next (unnumbered) equation ten lines below, the formula for "contrast sensitivity" is given. It is observed that contrast sensitivity is equal to eye sensitivity multiplied by the adaptation brightness, B.

There seems to be another misunderstanding in wording where Mr. Teele makes a comparison between the "open road visibility" as treated in the paper and "clear road visibility distance". The studies in the paper refer to visibility; - not visibility distance. In the introduction of the paper, I endeavored to make it clear that "full field visibility" as needed for safe headlighting is not the same as "visibility distance" of a single target as generally used in headlight tests. The two are not directly comparable for the same reason that single target laboratory seeing and seeing in actual practice are not the same. The visibility distance of a single target is a logarithmic function of the beam candle power. For that reason if the beam candle power should be reduced as much as one half (50 percent), the visibility distance of a single target is shortened only about 10 percent. Yet in reducing the candle power to one half, many objects and details throughout the full field may fall below the threshold of vision and thereby decrease the driver's knowledge of the situation ahead much more than 10 percent. This concerns the present study because a proportionate increase in opposing glare has approximately the same effect as a decrease in our beam candle power. So the experience cited by Mr. Teele that "with observer drivers engaged in headlight tests, it has been found that to obtain 80 percent of clear road visibility distance we can allow much more than 20 beam c.p. from oncoming headlamps", does not apply to full field visibility.

Then Mr. Teele points out that present sealed beam headlamps project 800 to 1000 c.p. toward the eyes of the driver and later, when discussing the fixation point, he sort of chastises motorists for not directing their eyes at the right-hand edge of the road in order to help alleviate effects of oncoming glare. Here Mr. Teele strikes the very heart of the present headlighting problem. Let us consider the full meaning of this. It is desirable for safety that the driver be able to see straight ahead of his course of travel and far enough ahead for making up his mind what to do in each successive situation. The direction straight ahead is his principal line of sight in the daytime and even at night when in clear road. Yet the best that can be done with the present headlighting system, when meeting another car, is to expect the driver to take his eyes away from the direction in which his car is traveling and look down at the right-hand edge of the road. This means that the only function of modern headlighting when cars meet is to keep in the track. The driver can only gamble on what is ahead. The situation is what Dr. Land, in describing Polaroid Headlamps in Highway Research Bulletin No. 11 (1948), called the "blind driving zone". So the answer to Mr. Teele's question as to why my analysis indicates that for near ideal headlighting the glare should not be more than 20 c.p., whereas present headlamps cause 800 to 1000 c.p. (40 to 50 times as much) is that the analysis studied in the paper is based on seeing the full field, including the directions straight ahead, whereas in tests of present headlights, consideration is given to only one target and drivers must be advised to look down at only the right-hand edge of the road.

The above mention of the deficiency of the present headlighting system is, in no way, a criticism of the engineering accomplishments shown by the precision manufacturing of the modern automobile headlamp which has culminated in the development of the sealed beam. It refers, rather, to the lack of general interest in, and appreciation of, what is actually needed for real safety as to night visibility on the rural highways.

The remainder of the points raised by Mr. Teele concerns mostly the test methods. It may be kept in mind that the purpose of the tests was merely to find a value for use in Holladay's glare analysis for balancing and comparing adaptation levels with and without glare. The value can be found in other ways, for instance, it can be computed by following the work of Stiles in England, but the test method seems direct and simple. After finding that the 50 c.p. glare caused the same adaptation level as did the headlighted roadway, the Holladay data were used from then on.

For the purpose intended, it was unimportant whether the tests were made from a moving or a stationary car out on a highway, in an undisturbed yard, or in an inclosed laboratory. The thing which was important and to which I tried to adhere was that the same pertinent conditions prevailed when measuring adaptation levels with eyes exposed to the headlighted highway and when exposed to the glare.

Mr. Teele calls attention to the importance of the background and fixation point. In all tests the line of sight of the observer was toward the target "T" which was straight ahead on the horizontal. Since the immediate background of the 1 deg. square target "T", as formed by the 1/2 deg. black border, was always below the threshold, the "brightness difference" of target and background was synonymous with "brightness" of the target. Moreover, since the target was just barely perceptible, its brightness had no appreciable effect on the adaptation of the eye. In the phase of the tests when facing the headlighted roadway, the adaptation state was established by the surround brightness which comprised only the headlighted roadway and environs adjacent to the fixation point toward target "T". In the other phase of the tests in the undisturbed yard, the adaptation state was established only by the brightness of glare lamp "G" also adjacent but further to the side of the fixation point toward target "T". Then following the Holladay method of analysis, the adaptation levels of both phases were added together for computing the adaptation level simulating actual driving conditions. The Holladay summation method is shown on page 2-20 of Illuminating Engineering Society Lighting Handbook (3). It is true, as Mr. Teele suggests, that the effect on adaptation level of the road surface brightness as illuminated by the other car was neglected. This would help silhouette seeing between the two cars, but would interfere still more with the seeing of road conditions beyond the other car.

There may appear at first to be a material discrepancy in the exposure time when testing for the least perceptible brightness of target "T" with eyes exposed to the different candle power values of glare lamp "G". During each run of this phase of the test procedure, the eyes were exposed continuously to some particular candle power glare, whereas in actual driving the glare source normally remains in the field for only a relatively short period. But what we were seeking was the one candle power glare value which caused the same adaptation state of the eye as did the headlighted roadway when looking straight ahead. Since this was found to be approximately 50 c.p. we know that in all tests against glares in the neighborhood of the 50 c.p., the adaptation levels were near the same as the adaptation level with eyes exposed to the headlighted roadway. So it made no material difference whether the eyes had been exposed to the 50 c.p. glare for a long time or to the headlighted roadway for a long time.

The reason for keeping the attention of the observer and the fixation point of his eyes directed straight ahead in all tests was that this is the direction in which the driver needs most to look in order to appraise, at ample distances, the destiny of his speeding car.

In Dr. Lauer's discussion, it appears by his first paragraph that he considers the problem of glare "for most drivers is not a crucial one" and he goes on to say, "A few persons are blinded badly by light . . ." Can it be that Dr. Lauer is oblivious of the problems of night visibility and the hazards of nighttime driving as consistently disclosed by the statistics from accident records? He seems to be talking about the rare occasions when motorists are totally blinded by headlight glare and whether they are bothered by discomfort of glare. In contrast, the scope of the paper is limited to the reasons for the depletion of vision which, with present headlights, occurs every time cars, traveling at normal speeds, meet each other on typical country roads at night. So our interests seem to be in different lines and in that respect the comments of Dr. Lauer are, in the main, irrelevant to the subject matter of the paper.

Because of the above divergence of objectives and the carelessness of his reading of the text, as repeatedly displayed in the looseness of his misquotations, there is no wonder that Dr. Lauer keeps talking about "confusion". For example, he purports to make a quotation that, "it is possible to maintain the same order of visibility when cars meet", which anyone as well as Dr. Lauer, would naturally question. This misquotation is evidently taken from the Synopsis, third paragraph, where the sentence begins, "It is possible to maintain the same order of visibility when cars meet, provided . . ." Dr. Lauer stopped the sentence at the comma to exclude the modifying clause. The proviso in the statement, as carried throughout the paper, is that adaptation level be kept near the same when meeting cars as when not meeting cars. This is the essence of the analysis.

Then he mixes my statements regarding the 20 c.p. and the 800 to 1000 c.p. as though they both were intended for a measurement of the same thing. In the article of the paper titled, "Measurement of Differential between Meeting Visibility and Open Road Visibility", second paragraph, it was reported that the analysis indicates the need of keeping glare down to 20 c.p. for desirable visibility when cars meet. The next paragraph starts out, "By way of comparison . . .", merely to illustrate that headlamps now on the roads cause 800 to 1000 c.p. glare which is 40 to 50 times as much as the desirable 20 c. p.

Next Dr. Lauer recites the relationship between candle power, foot candles and distance as found in elementary text books even on general physics. Holladay (2) pointed out that, on a straight roadway the problem of glare can be simplified by considering only the candle power of the source of glare. It is simply that as an oncoming glare car comes closer, to thereby increase the glare in proportion to the foot candle illumination, at the same time the angle between the direction of the glare source and the line of sight, straight ahead, gets wider. The two opposing influences neutralize each other so we need to consider only the candle power of the glare source (Fig. 1).

Of course Weber's law and Fechner's law are not the same. I referred to Weber's fundamental law because it may give some concept of the magnitude of the changes in eye sensitivity which is the basis of the study in the paper. But this has no connection with Fechner's addition to Weber's law. It again may be noted that because Weber's law shows the product of prevailing brightness and eye sensitivity to be a near constant, it can explain the magnitude of the large changes in eye sensitivity which in conformance with this law, must occur under the large changes in the prevailing brightness. (Note: The prevailing brightness includes the opposing glare.) Although Weber's product departs from a constant at the low levels encountered in headlighting, its rate of decrease is only 1/25th of the proportionate rate of decrease in prevailing brightness. So a change in prevailing brightness continues to cause a large change in eye sensitivity. Eye sensitivity is defined (Eq. 1) as the reciprocal of minimum perceptible sensation. Weber's law refers only to the relationship of stimulus to this minimum perceptible sensation. Fechner's law states the relationship between the stimulus and intensity of sensation when above the threshold concerning which we are not involved in the present study.

If it is the symbol S to which Dr. Lauer objects, it may be noted that in Fechner's formula, stimulus is often represented by the symbol S. However, sensation and sensitivity also begin with the letter S. In the particular algebra included in the paper, the meaning of the symbol S is clearly defined at the beginning of the Appendix which seems sufficient for the problem at hand. Perhaps, however, I should have thought of another symbol. This seems like a trivial point but it would be unfortunate if the contributions which the psychologists can make toward safer headlighting should be hampered merely because of different customs in the use of symbols in simple mathematics.

Dr. Lauer brings in an instructive point in regard to the precision of the testing. My testing did not have refinements procurable where more elaborate laboratory facilities are available. But in the present study the extra effort required for more refinement does not seem warranted because measurements of visibility involve other wide variables and uncertainties. While Holladay's formulas can serve in the solving of the major problem of headlight glare they are, after all, empirical and not intended for detailed precision. More exactness would, in itself, be interesting but we are so apt to get intrigued with our own test technique as to miss seeing the forest for the trees.

No doubt the change in color of the filaments toward the red as dimmed by the rheostats contributed some error. Photometric calibrations were made with a barrier layer photo-electric cell.

Dr. Lauer further advises revision of the terminology in conformance with more conventional usage. Effort was made to avoid that very thing lest the essence of the analysis be lost. Ordinarily, as mentioned above, the capability of the eye to adapt itself to the prevailing brightness helps seeing but in automotive night seeing that adaptation action, being dominated by the opposing headlight glare depletes, rather than aids, the seeing process. So it seems necessary to get back to some fundamentals which properly can be omitted in most problems of seeing.

REFLEX REFLECTOR PERFORMANCE CRITERIA

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SYNOPSIS

There has been an increasing interest in the field of reflex reflector photometry during the last few years because of the tremendous increase in the number of these devices that are used for roadway delineation and motor vehicle marking. Reflex reflectors are special types of mirrors which have the characteristic of returning a substantial fraction of the incident light toward the source from which it originates regardless of the incident angle. Because of their peculiar optical characteristics reflex reflectors appear very much brighter than even the best of white paints when illuminated under similar conditions and are thus very useful in marking roadway obstacles.

There are a number of different types of reflex reflectors, and each type has its own set of optical properties. It is necessary for reflectors to meet minimum performance specifications which have been drawn up by several purchasing and enforcement agencies. Because of the differences in the optical properties of various types of reflectors and the different methods of evaluation of these devices, a situation has developed in which the measurements among different laboratories do not always agree. This situation has prompted the investigation that is reported in this paper.

A review of the visual methods of appraisal has been prepared together with typical data showing the variations found when the human eye is used as a measuring instrument. A Photoelectric photometer is described which permits the physical measurement of the light flux from reflex reflectors when they are used under conditions which approximate field usage. A study of the variables affecting the measurements has been made using the photoelectric device. Data are shown for the changes in specific intensity when the different types of reflectors are used under varying conditions of divergence angle, entrance angle, orientation angle, test distance, size of light source, size of reflector, size of receiver and color of light source. It is shown that the geometry of the test set-up and the color of the reflector are quite important when measurements among laboratories are to be compared. A recommended test procedure based upon standardized conditions is outlined.

During the last few years there has been an increasing interest in the field of reflex reflector photometry because of the very large number of these devices used for marking roadway obstacles and vehicles. Reflex reflectors are special types of optical mirrors which have the characteristic of returning toward the light source a substantial fraction of the light that is incident on the reflex reflector, regardless of the angle at which the light strikes the device. Thus a reflex reflector is different from an ordinary mirror because of the direct return characteristics of the beam. Such devices are very helpful in marking roadway obstacles, delineating the sides of roadways and in acting as warning devices for parked vehicles or otherwise unlighted obstructions because these reflex areas will appear to be many times brighter than even the best white paints when illuminated under similar conditions.

There have been a number of different types of reflex reflectors developed during the past twenty years. Each type of device has somewhat different optical characteristics, but all have the same basic function. Therefore in practice it has been a problem for highway designers, motor vehicle equipment engineers, safety engineers and enforcement officials to decide upon the type of reflex unit to use for a particular application and to prescribe the performance requirements for the device. As a result of this situation a number of different specifications have evolved and a number of different testing techniques have resulted. The present status then is that a manufacturer of a reflex device may find that his device may comply with specifications when tested with one technique but may be much below specifications when tested with another technique. This is a very disturbing situation for both manufacturer and user of the device.

Before reviewing the existing techniques that are available for making measurements on reflex reflectors, it is perhaps best to review the developments that have occurred since the first devices were commercially manufactured. The original ideas associated with the design of reflex units are quite old and probably go back to the first observations of the eyes of wild animals at night when the observer was sitting close to a fire in the woods at night. In this case the lens of the animal's eye and the retina of the eye act as a redirecting optical system which returns part of the incident light in the same general direction as it came. Therefore the observer sitting near the fire could see a virtual source of light in the animal's eye which was really a reflection of the light source near which he was sitting. This idea was incorporated in the first lens mirror button type of reflex reflectors that were developed (see Fig. 1). A complete description of

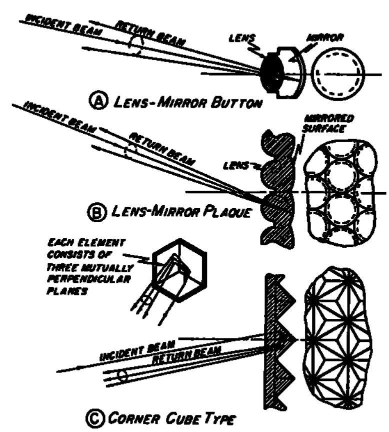


FIG I-TYPES OF REFLEX REFLECTORS

the optical properties of these devices will not be given here but can be obtained by reference to the literature. (1)[1] The lens mirror button system was then extended to an all glass plaque in which the lens and mirror were cast on one base with the rear surface of the plaque coated with a reflecting material such as silver or aluminum. Another type of optical device developed at about the same time employed the principle of the parallel return of the reflected beam from three mutually perpendicular plane mirrors. This may be thought of as the corner of a cube and devices using this principle are generally re-

[1] Figures in parentheses refer to references listed at the end of the paper.

ferred to as corner cube reflex reflectors. The reflector may employ a single large corner cube or may consist of a mosaic of a large number of small elements.

The original designs all employed glass refracting materials and in the automotive and highway field these elements were generally used as cast or molded. Because of economic considerations, it was generally not possible to use polished optical parts. Therefore, because of the slumping and shrinkage characteristics of molded glass parts it was not possible to obtain high optical precision. Thus the first reflex units generally had a return light pattern which was spread out over relatively wide angles. It may be noted that the intensity of the return beam of light is dependent upon how tightly packed the return flux is within a small cone angle. As the cone angle of the return flux is made smaller and smaller, the intensity of the light increases. This is similar to the condition that prevails when water is forced through a nozzle. If the emitted water cone is large, the water is not projected very far; but if the nozzle is adjusted to restrict the solid cone to a small jet the water will be projected to a much larger distance.

The material used for all of the reflex elements manufactured up to about 1939 was molded glass and therefore had the generally wide angle returned light pattern. Since 1939 plastic materials have been used to a greater extent for reflex devices; and, since the molding characteristics of plastic are very much different than those of glass, it is possible to make large volume production moldings out of plastic which have extremely high optical precision. Thus during recent years there has been a general change in the light distribution in the returned beam from reflex reflectors. It is now possible to have a reflex unit so well made that a device would not be effective as an automotive signal because too much of the flux would be returned exactly co-incident with the source of light. We need therefore to review the performance of reflex reflectors to be certain that the devices function in a manner which will be suitable for the service for which they are intended.

The original specifications for reflex units were primarily written for automotive marking devices. Therefore, the range of visibility distances that were considered important were in the order of fifty feet to five hundred feet. As these devices began to be applied to highway obstacles it was generally agreed that longer visibility ranges were important. There are applications in which reflex reflectors are being applied to informational signs, to large area obstacles and for advertising purposes. Under these latter circumstances it is desirable to have materials which have wide angle return light characteristics and also which will accept wide angles of incident light. Thus there appears to be a need for devices and specifications covering three different types of services - namely, long range visibility, intermediate distance visibility, and wide angle visibility.

Present Status of Reflex Testing -Testing techniques have been developed to give a measure of the visibility distances and the over-all efficiency of reflex devices. The systems incorporate ideas associated with visual brightness balancing, visual balancing of the total light flux, and photoelectric measurement of the light flux within restricted directions, and photoelectric balancing of the total reflected light flux. These various procedures give results that are subject to different interpretations. For instance, a technique that evaluates the total return flux from a reflector may give a measured value that is identical for two different makes of devices, but because the distribution of the return light is different in these two devices the roadway appearance of the units may be entirely different. Similarly, a technique which presumes to evaluate the long range visibility may give results on two devices that are markedly different but when field tests are made the units may appear to be very similar. Thus it is highly desirable to analyze the variables in the testing techniques so that a method may be evolved which will satisfactorily appraise various types of reflectors for any service to which they may be subjected.

The early testing techniques were developed around a visual comparison between a standard lamp and a reflex reflector. The schematic arrangement for such a set-up is shown in Figure 2.

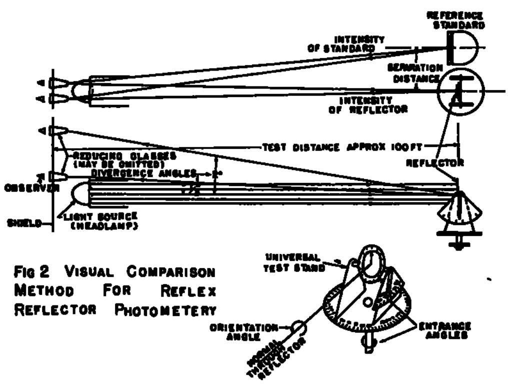


Fig 2 Visual Comparison Method For Reflex Reflector Photometery

A procedure of this type was outlined in the S. A. E. "Handbook of Recommended Practices" as long ago as 1936. This procedure established observation stations at divergence angles of 1/3 deg. and 2 deg. and thus recognized the importance of intermediate signaling distances up to 500 ft. as well as the shorter range and wide angle visibility requirements within 50 ft. During the initial phases of the establishment of these S. A. E. specifications there were inter-laboratory comparisons made to determine the adequacy of the method and the precision with which results could be duplicated. The devices that were used as reference standards and as inter-laboratory checking samples were made of glass and had the characteristics of glass units that have been previously referred to, namely, relatively wide angle return flux distribution and transmittance characteristics that were similar to the filters on the comparison standards. It was therefore possible to obtain what was considered to be reasonable inter-laboratory checks using this system (total variation of approximately 30 percent). When the newer plastic materials were substituted for glass however, it was observed that the differences among the laboratories increased almost immediately. This has led to the present examination of the problems involved.

PROBLEMS OF MEASUREMENT

As a first consideration in the photometry of reflex reflectors, it is necessary to examine the magnitude of the light flux that is available for measurement. In general, reflex reflectors for automotive and highway service are illuminated with very low densities of light flux. For example, a reflex reflector on a truck at 500 ft. may have as much as 0. 10 f. c. illumination considering that the truck is in the main portion of a sealed headlamp beam. If it is out of the main portion of the beam as is most likely then this value may drop to 0. 01 f. c. or even very much less. If the reflector is being used for roadway delineation the illumination at 1000 ft cannot possibly exceed approximately 0. 06 f. c. and is generally very much less than this value. Even at distances of 100 ft. or less from a pair of automobile headlamps the illumination will not ordinarily exceed 0. 50 f. c. because at these distances and at the usual mounting positions the reflector is out of the high intensity portion of the headlamp beams. Therefore, it is an unusual case when a reflector would have as much as one f. c. illumination as prescribed by the S. A. E. standard test procedure. With such low levels of illumination as previously mentioned and considering the inherent inefficiency of devices of this type, particularly the colored reflex reflectors, it is at once apparent that the light flux available for measurement is extremely small. Consider, for instance, a three inch diameter crystal reflector at 100 ft. with 0. 50 f. c. illumination. The total flux received by the reflector would be approximately 0. 024 lumens. If the device has an overall efficiency of 50 percent and returns the light flux within a 1-deg. cone angle, the average intensity would be 0.50 c.p. At 100 ft. this candle power would produce 0.00005 f.c. illumination. The small amount of energy available for measurement led to the establishment of the visual techniques because it has only been within recent years that even reasonably stable high sensitivity photoelectric devices have been available for making such measurements.

The visual technique of making measurements will be described in some detail in order to emphasize the variables that are involved and the controls that are required if duplication of readings is to be obtained. In order to discuss the quantities to be measured and controlled, it is necessary to define some of the special terms that are used in the photometric procedure. It will be helpful to refer to Figure 2 for a clarification of the following terms.

Specific Intensity - the candlepower of the reflector per foot-candle of incident illumination on the reflector. The intensity (candle power) of the reflector will be directly proportional to the incident light flux density (foot-candles) so for reference it is convenient to refer all intensities to a unit illumination.

Divergence Angle - the angle at the reflector between a line through the center of the light source and a line through the observer position. This is used to measure the distribution of light in the return beam.

Entrance Angle - the angle at the reflector between the line through the center of the light source and the normal to the plane of the reflector. This is used to measure the effectiveness of the reflector when illuminated from different directions.

Orientation Angle - the angle in the plane of the reflector between a reference mounting position and the angle through which the reflector may be rotated about its normal axis. This is used to measure the effectiveness of the reflector when mounted in different rotational positions.

Measurements at these three angles will, in general, determine the characteristics of the reflex reflector. There is one other angle, the azimuth angle, which may be important in some cases. This angle refers to the position of the observer's eyes with respect to the light source. The observer may have his eyes at any of the reference positions indicated by the hands of a clock when viewing the reflector from behind a headlamp. For instance, the normal observation position is at 12 o'clock. The location, however, may be at 3 o'clock, 6 o'clock or 9 o'clock or at any of the other intermediate positions. For most reflectors, this is a relatively unimportant variable, but it may be necessary to consider it in some cases.

There are four main parts of the set-up that need to be examined in visual testing: (1) the light source, (2) reflex reflector, (3) reference standard, and (4) the conditions at the observation station.

First let us consider the variables associated with the light source. The factors that can change are: (a) the color temperature which affects the spectral distribution, (b) the size, and (c) flux density distribution within the beam.

At the reflex reflector, we have the following variables to consider: (a) the pattern of the return light flux. This is associated with the optics of the design, (b) the materials from which the unit is made. This will normally involve either transparent glass or transparent plastic materials. It may be noted that plastic materials are subject to polarization which may further complicate a testing procedure; (c) the color of the return flux. This will have to be given critical attention, particularly since plastic materials have entirely different types of transmittance curves than do glass units; (d) the surface conditions of the reflector. Solarization and aging will require that new and weathered devices should be examined; and (e) the orientation of the reflex both for entrance angle and orientation angle.

The reference standard should be completely specified as to: (a) the details of its construction and its calibration; (b) the size and methods of varying the size may be important; (c) the method of variation of the light in the standard will be extremely important. Thus, if current variation is used a change in color may result whereas if a change of distance is used the size may vary. There are methods of avoiding both of these difficulties that will be described later; (d) the transmittance characteristics of the color filters employed on the standard will have to be known and specified; and (e) the separation distance between the reflector and the comparison lamp should be given.

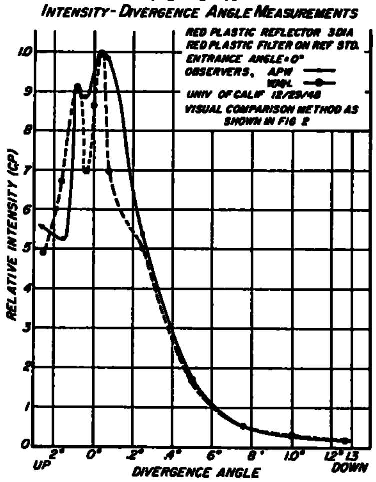


Fig 3

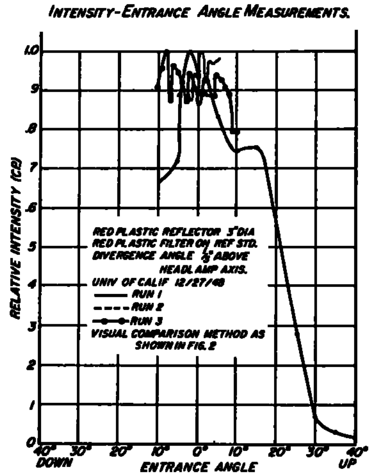


Fig 4

At the observation station the important variables will be: (a) the test distance, (b) the divergence angle, (c) the size of the reflector, (d) monocular or binocular vision, (e) the use of optical enlarging or reducing lenses, (f) the adaptation level of the observer must be considered since visual spectral response functions as well as visual sensitivities vary from one adaptation level to another, and (g) the method of making the comparison, that is the method of balancing the standard against the reflex, must be specified. It is possible to vary either the reference standard or the reflector. Both systems are being used. The standard may be varied by the use of current changes, rotating sector discs, neutral filters or distance changes. The reflex reflector may be varied by changing the aim of the headlamp, changing the current in the headlamp, use of rotating sector discs in front of the headlamp, or by the use of neutral filters.

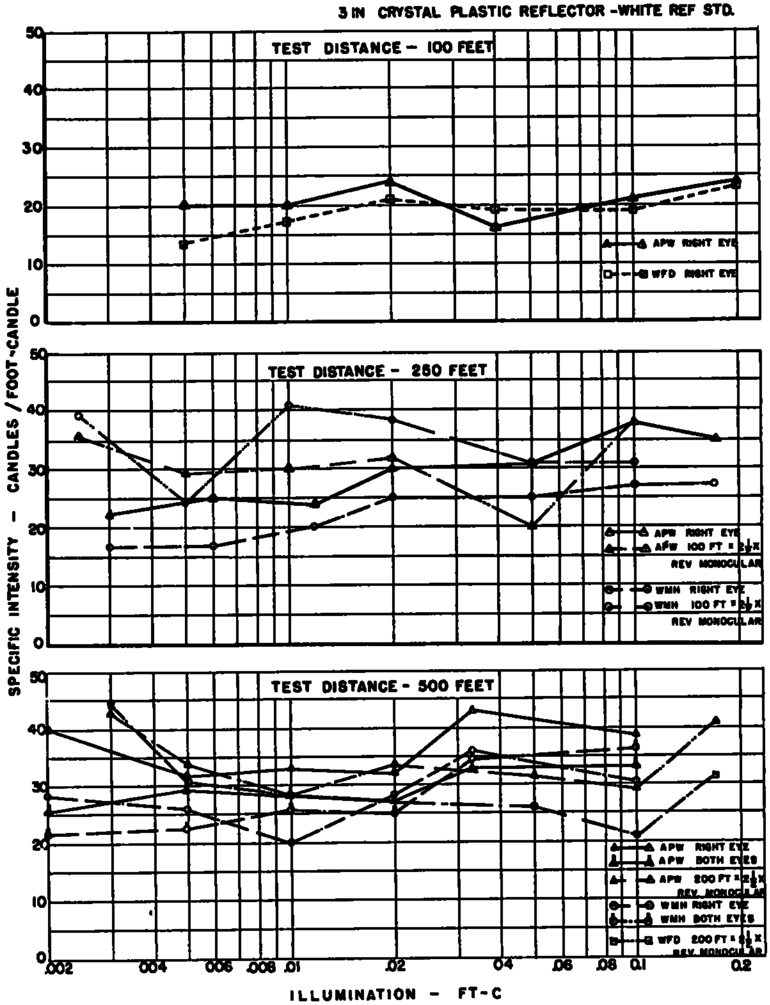
The mere listing of all of these quantities indicates the complications that can arise because of the possible combinations of all of the variables. It is necessary therefore to isolate the effect of these different variables to determine which are important and which may be set aside as unimportant. It is believed that the differences that are reported in the measurements among the different laboratories are largely due to the differences in the techniques and the laboratory set-ups that are used. This has become quite evident in recent months during which time a set of reference standard reflectors has been re-circulated among the laboratories for a re-evaluation of their systems. The initial test results yielded the expected wide variations, but as more re-tests were made and as each laboratory became familiar with the procedures used in the other laboratories the results began to be more consistent. (Refer to Appendix A.)

In an attempt to isolate the effects of the above variables a series of studies were inaugurated using the conventional visual appraisal methods. Data were taken to attempt to evaluate the divergence angle characteristics of different types of reflectors, the effect of entrance angle, the effect of test distance, the variations that resulted from a change in size of source, size of reflex reflector, and size of the receiver. Other tests were made to attempt to isolate the effect of color and the effect of the separation distance between the reflex reflector and the comparison standard. Typical data on the results of these visual observations are given in the curves of Figures 3, 4 and 5.

These data are reported because they represent the results of carefully controlled attempts to visually evaluate the variables mentioned. It was felt that, after studying the data and after a review of all of our past data and experience with the visual technique, the only reasonable conclusion that can be drawn from the data in these figures is

FIG.5 VISUAL METHOD - DATA

INTENSITY vs LEVEL OF ILLUMINATION / TEST DISTANCE / USE OF REDUCING GLASSES / MONOCULAR & BINOCULAR VISION



that the variations among observers and the variations in the data of each observer are so large that the effect of the variable being investigated is not apparent. Some trends are indicated, such as the change of apparent intensity with distance, but because of the large scatter it was felt that such trends should not be considered. These data show the problems of visual heterochromatic photometry at extremely low levels of adaptation. Other researches at low adaptation levels have corroborated these results. It is generally conceded that duplication within ± 15 percent of the mean is all that may be expected. Such tests as shown together without past experience in the laboratory, are the basis for the general policy of using a 30 percent tolerance on the minimum specifications. The scatter of the data obtained by the visual technique also clearly point to the need for a satisfactory physical method for making reflector measurements.

A PHYSICAL REFLEX REFLECTOR PHOTOMETER

The design specifications for a physical photometer to measure reflex reflectors were set up from ground rules established to measure the performance of all types of reflectors as follows: (1) The photometer should permit an evaluation of a reflector for any type of service to which it may be subjected. (2) The instrument should be capable of measuring a minimum performance device at the greatest entrance angle and largest divergence angle to which it may be reasonably expected to be used in service. This was arbitrarily set at a specific intensity of 0.01 candle power/foot-candle at a 2 deg. divergence angle and at an entrance angle of 30 deg. (3) The receiver of the photometer should not be any larger than the lens of an average eye and should be located at least 100 ft. away. (4) The photometer should be used in such a manner that the color response of the receiver will not be important or else the color response should be corrected to that of the average photopic eye. (5) The device should be readily calibrated and should be stable within the period required for a test. (6) Range changing means should be provided so that maximum performance reflectors as well as minimum performance devices can be evaluated. (7) The divergence angle measuring means should permit measurements taken between 0.10 to · 2.0 degrees.

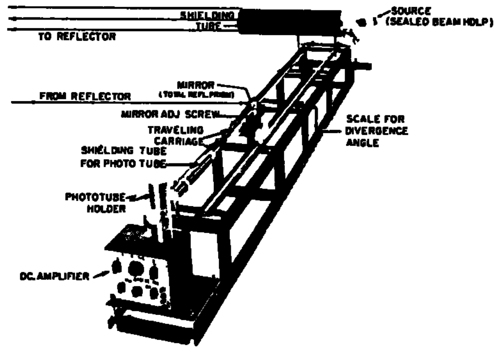


Fig 6–Reflex Reflector Photometer

Such an instrument was constructed and is shown in the photograph of the equipment in Figure 6. A schematic diagram of the test setup is shown in Figure 7. For reference a circuit diagram is given in Figure 8 and calibrations of the equipment for both sensitivity and color response are shown in Figures 9 and 10. An analysis of the electrical circuit is not required for this paper, but it may be stated that the circuit has permitted the sensitivity requirements set forth in the ground rules to be readily obtained. Furthermore, the circuit is very stable and is quite insensitive to fluctuations in battery voltage or filament current. The photo-electric device shown has been a major development of this research investigation. It should be pointed out that, while the sensitivity and stability are quite satisfactory, the color response is not adequate for use of this instrument as an absolute device for measuring luminous flux. The photometer is only satisfactory if used as a comparison device in which the flux to be measured and the calibration

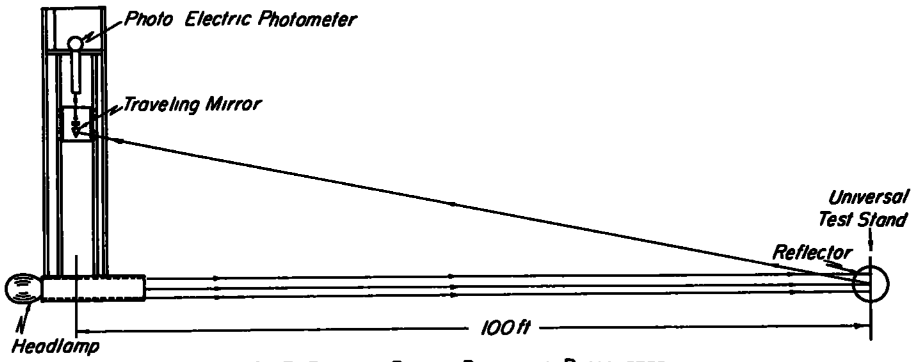


Fig 7 - Physical Reflex Reflector Photometer

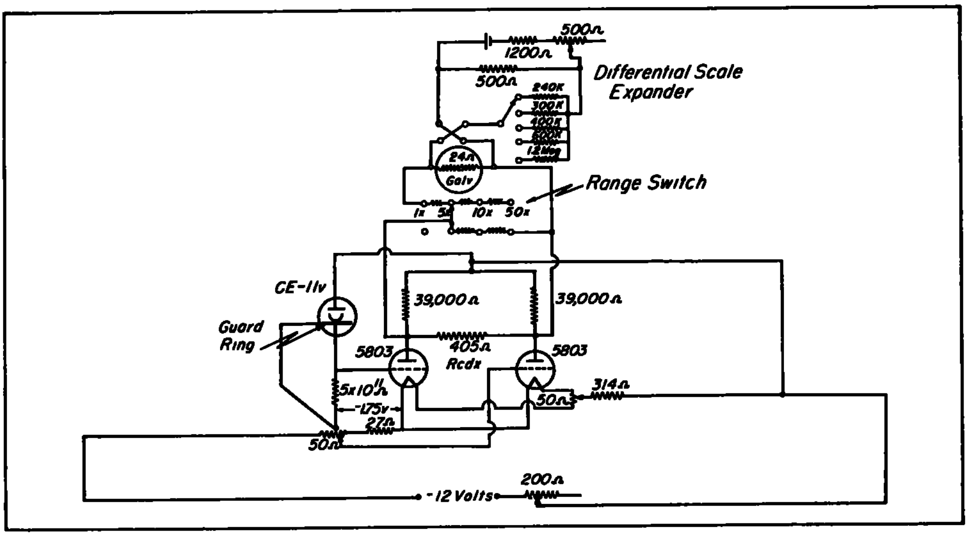


Fig 8—Circuit Diagram - Photo tube Amplifier

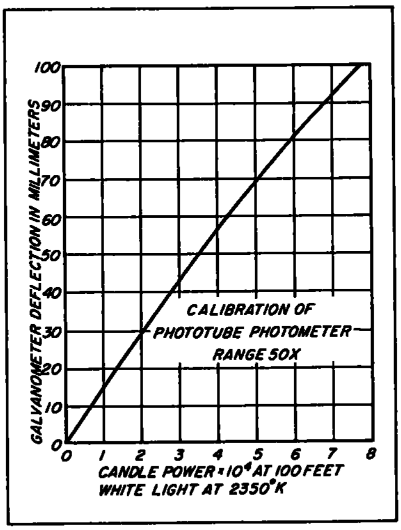


Fig 9 - Calibration Phototube Photometer

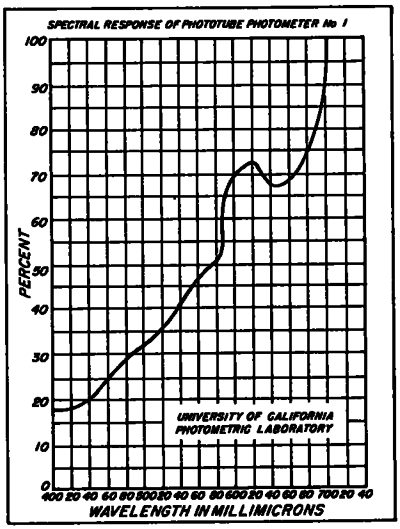


Fig 10-Color Response -Phototube Photometer source have the same spectral distribution so that the color response characteristics cancel out. The method of measuring the intensity at different divergence angles is shown in Figures 6 and 7. By the use of the traveling mirror on the track the photometer can be mounted permanently and aligned carefully with respect to the headlamp. The divergence angle characteristics can be obtained for any position of the reflex reflector within a few minutes with such an arrangement. Thus it is possible to carefully analyze even the lowest output reflector at distances and under conditions which can be made to truly represent field performance.

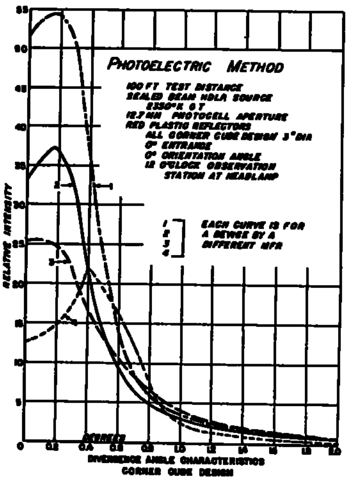


FIG 11

CHARACTERISTICS OF REFLEX REFLECTORS

The physical distribution photometer described above has been used to isolate the reflex reflector variables that were mentioned in connection with the visual technique. By the use of this physical instrument, the scatter of the data that was previously reported for the visual techniques can be eliminated. Therefore, the effects of each variable can be shown.

Divergence Angle - It was first considered desirable to determine whether or not differences in return flux distribution could be observed from different optical designs of reflex reflectors. Several devices representing all types of commercially available reflectors were measured. These results are shown plotted in Figures 11 and 12, and represent corner cube construction, lens mirror construction, and beaded surface types. It may be noted from the curves that the divergence angle characteristic of reflectors made by different manufacturers are substantially different, and that each general classification may be also differentiated from the other. In general, corner cube construction yields higher intensities at smaller divergence angles and at small entrance angles than does either the lens mirror or the beaded surface type. The lens mirror type is intermediate between the beaded surface and corner cube designs in this respect.

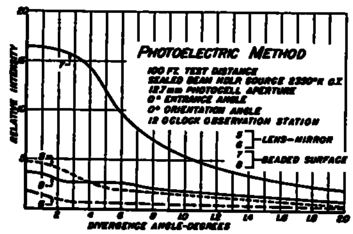


Fig 12 - Divergence Angle Characteristics

The divergence angle characteristics of a reflector will determine the type of service for which it is best suited. Devices that have high specific intensities at small divergence angles (0. 10 deg. to 0. 33 deg.) are suited for long distance signaling as in roadway delineation. Devices which have moderately high specific intensities at divergence angles in the order of . 33 deg. to 1. 0 deg. will be better suited to intermediate service applications such as in automotive equipment. These devices should also hold up reasonably well in specific intensity at divergence angles as great as 2 deg. For the type of service required in signing and advertising or in marking large areas the divergence angle characteristics may be very much more uniform, between 0 deg. - 4 deg. For such service the intensities at large entrance angles should also hold up very well.

Entrance Angle - The effect of changing the entrance angle is shown in Figure 13 for several types of commercially manufactured reflex units. The type of construction is indicated on the curves in the figure. It may be noted that the entrance angle characteristics show a larger percentage change between 0 deg. -30 deg. for corner cube construction than for lens-mirror types, but the total amount of light reflected by corner cube devices is generally much more than for other types even at large entrance angles.

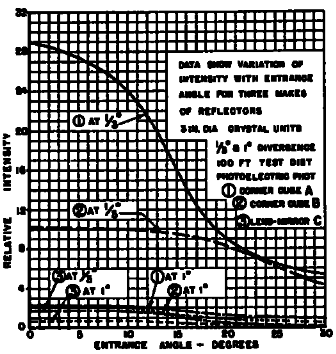


FIG 13 ENTRANCE ANGLE CHARACTERISTICS

Orientation Angle - In studying the light distribution of the return beam from various types of reflectors, it has been noted that the flux is not generally symmetrical about the axis of the return beam. In some cases the pattern consists of bundles of distinct rays emitted in the general direction of the source of light. Thus, if the plane of measurement at different divergence angles happens to be through one of the regions of high light flux, the values of specific intensity will be high; but if the device is rotated about its normal axis the plane of measurement at different divergence angles may fall in a region of very little return light flux. Data on these effects are shown in Figure 14. As shown, some devices may have a symmetrical pattern while others may be completely asymmetric. It is important to note that if a device has an asymmetric pattern it is extremely important to have the device oriented properly in its mount in order to perform satisfactorily.

Test Distance - There has been considerable speculation in the effect of test distance on the measurement of specific intensity. Normally, the distances encountered in the field are greater than 100 ft., but because of laboratory space and the dimensions of available darkened areas it has usually been necessary to reduce the laboratory test distance to 100 ft. or less. The test distance is considered to be important largely because of the change in the geometrical relationships among the optical parts rather than because of the

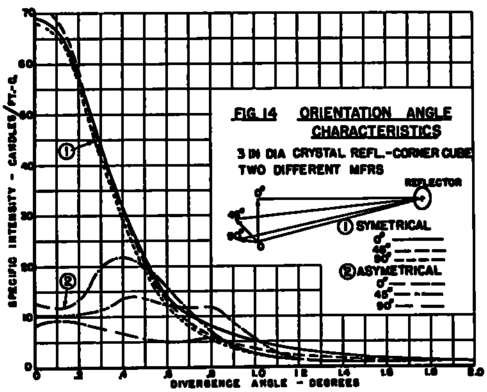
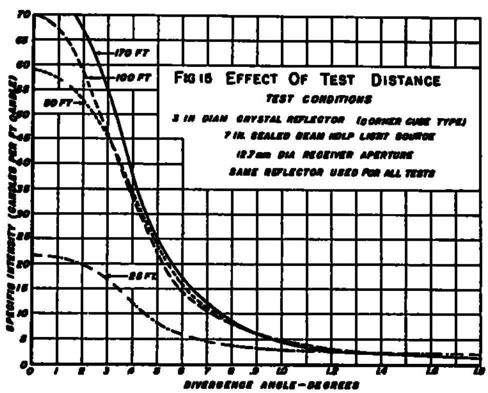


FIG 14 ORIENTATION ANGLE CHARACTERISTICS

absorption and scattering effect of the atmosphere. For very long ranges and under adverse weather the latter may be quite important. In order to evaluate the effect of test distance, measurements were made on the same units at different distances under controlled conditions. The data shown in Figure 15 give the results of these tests. These data may be summarized as follows: As the test distance is increased, keeping the size of reflector, light source and receiver size constant, the specific intensity at small divergence angles tends to increase. This is explained by the fact that the change in geometry causes the receiver to evaluate a smaller spread of divergence angles as the distance increases. The receiver will give an average value for the complete bundle of rays that it intercepts. For instance, at a 100 ft. test distance using the sizes of elements shown in Figure 13, the specific intensity reported at a setting of 0.33 deg. represents an average of the flux between 0.17 deg.

to 0.50 deg. divergence angles. At a 50 ft. distance the range of divergence angles measured would be from 0.00 deg. to 0.67 deg. and at 200 ft. the average would include divergence angles between 0.25 deg. to 0.42 deg. Thus for reflectors having a divergence angle-intensity curve with a steep slope, more representative measurements will be made at greater test distances. The data shown for the 25 ft. test distance are not considered to be reliable because of the difficulties in alignment, measurement of angles, and the non-uniformity of the illumination on the reflector. The values are probably too low but are generally in the right direction.



Size of Light Source - Since most reflex reflectors that are being discussed in this paper will be used under automotive service conditions, it is proposed that an automotive type headlamp should be used as a source. Here again because of laboratory arrangements it may be more expedient to use a different light source having a different beam distribution and a different size of aperture. The effect on the specific intensity of changes in size of light source are shown in Figure 16. These data may be interpreted as follows: The results are similar to a change in test distance. As the size of source is reduced, other conditions remaining constant, the bundle of rays intercepted by the receiver includes a smaller range of divergence angles. The average value of the intensity in the region of the curve where the slope is greatest, tends to be higher for the smaller divergence angle return beam from the small source than for the larger divergence angle return beam from the larger source. The overall effect is a decrease in the slope of the curve due to the averaging of overlapping relatively large cones of light coming from the larger source.

Size of Receiver - In actual use the receiver of the return flux from a reflector will be a motorist's eye. Thus for all observation distances in the field the size of the receiver is fixed by the dimensions of a normal eye. The eye

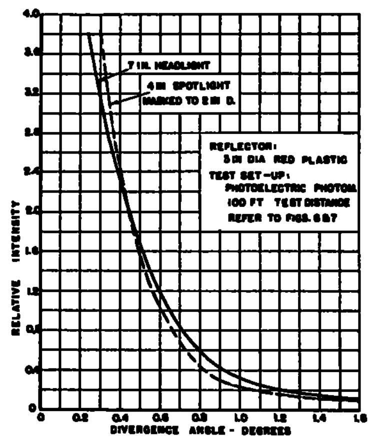


FIG.16 EFFECT OF SIZE OF SOURCE

lens aperture is approximately 7 to 10 mm. diameter. In all evaluation techniques, except those employing direct binocular vision, the size of the receiver may not be the same as in typical service conditions. In most cases the receiver will intercept a substantially larger solid angle than is intercepted by the motorist's eye. This has an effect which is similar to changes in size of source, size of reflector or test distance. It is a matter of intercepting a different cone of light than is intercepted by direct visual appraisal. If a larger cone angle is received, the measurement will represent an average of a greater range of divergence angles than if a small cone is received. Data on this variable were not taken during this investigation because the effect of changes in receiver area would be similar to those previously reported under Test Distance and Size of Light Source. All of the data were taken with a receiver having an aperture of 10 mm. diameter.

Color of the Source - The spectral distribution of the light flux may have a considerable bearing on the performance of a reflector. This effect may be expected to be large when colored devices are considered, but may or may not be so important when crystal or uncolored reflectors are being considered. The data showing the effect of changes in color temperature of the light source for crystal reflex units using the photoelectric photometer of Figure 6 are shown in Figure 17. The photo cell used in this photometer (Fig. 6) has a high response in the red re-

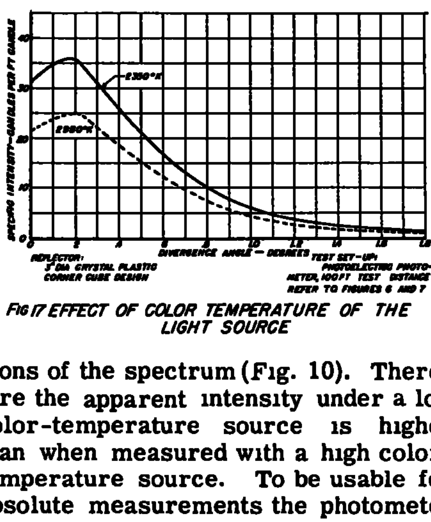
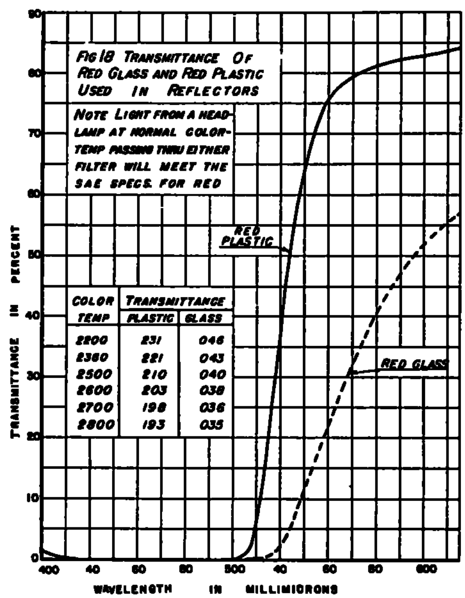


FIG 17 EFFECT OF COLOR TEMPERATURE OF THE LIGHT SOURCE

gions of the spectrum (Fig. 10). Therefore the apparent intensity under a low color-temperature source is higher than when measured with a high color-temperature source. To be usable for absolute measurements the photometer must be calibrated with a reference standard having the same distribution as the return beam from the reflector. This scheme is practical for un-colored reflectors but may not be possible for colored devices. It is proposed that a reference color-temperature of 2360 deg. K should be used for all reflex reflector calibrations. Most of the field observations of reflectors will be made under low adaptation levels in the region of the Purkinje shift in the visibility function. If a reference standard of 2360 deg. K is used the photopic visibility data may be applied. This has been the reference standard used to establish the conversion data to the scotopic region. (2)

Color of Reflex Unit - As previously mentioned, the transmission characteristics of the un-colored reflex reflectors may be sufficiently non-selective to permit measurements to be made with a fairly wide range of light source color temperatures provided that calibrations for the color temperatures are avail-



COLOR TEMP	TRANSMITTANCE PLASTIC	TRANSMITTANCE GLASS
2200	231	046
2360	221	043
2500	210	040
2600	203	038
2700	198	036
2800	193	035

able. However, when colored glass or plastic materials are used the transmission characteristics of these materials are very different than for crystal reflectors and the uncolored calibrations cannot be used except for relative measurements. It should be pointed out that even though two colored lights appear to be the same insofar as their color sensation is concerned, the spectral energy distributions may be quite different. Thus, unless colored lights are appraised with a device that exactly duplicates the average visual response curve, the resulting measurements may not bear any valid relation to the visual appearance of the lights. This would indicate that if physical measurements are to be made upon reflex reflectors, the measurements should all be made in terms of uncolored units. To evaluate colored reflectors it would then be necessary to determine the spectral transmittances of the colored materials and to calculate from these a factor to apply to the uncolored measurements. Typical spectral transmission data for materials used in reflectors are shown in Figure 18 together with the calculated transmittances for lights of various color temperatures.

that are or have been in general use. These are described briefly as follows:

Visual -

1. Modified Visual Method - The schematic diagram is as shown in Figure 19A. This system uses a short test distance but employs a mirror to obtain the recommended 100 ft. test distance. The illumination on the reflector is changed by placing apertures over the headlamp. The intensity of the standard is changed by varying the current through the reference standard.

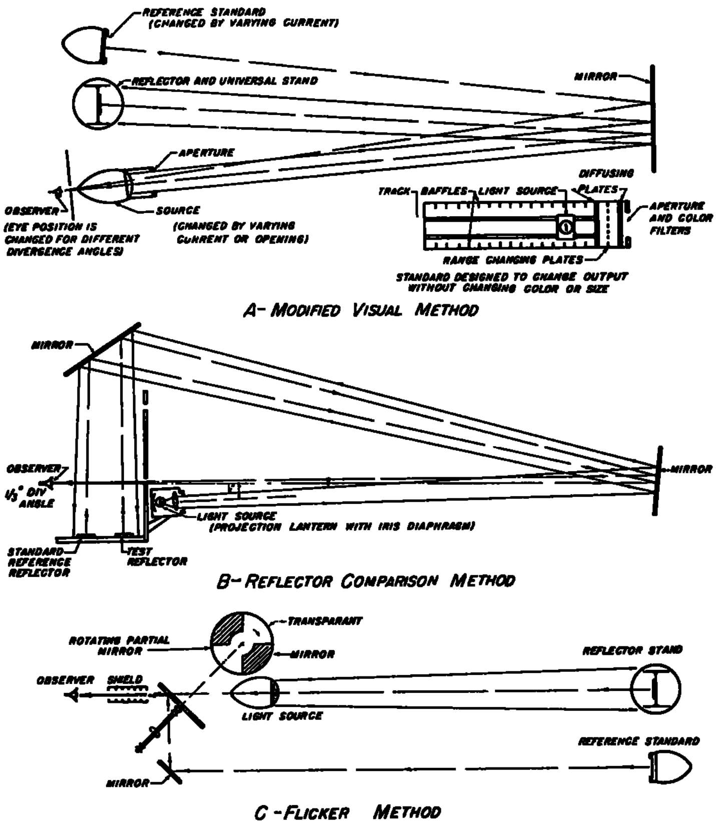


FIG 19 VISUAL COMPARISON METHODS

REVIEW OF EXISTING TEST PROCEDURES

In addition to the visual technique shown in Figure 2 as used at the Testing Agency for the California Highway Patrol at the University of California, there are a number of other techniques

The principal sources of error with this system are:

a. variations in the mirror,
b. changes in the size of source due to the apertures, and
c. changes in color of the source due to current variation.

These errors can be reduced to a minimum by using a good quality mirror; using a system of screens or other means to change the output of the source without changing the effective size; arranging the standard so that its intensity can be varied without changing either its size or current as indicated in Figure 19A insert. When these precautions are taken the technique is satisfactory if enough observations are made with a sufficient number of observers to obtain statistically reliable data. This is usually slow and costly.

2. Reflector Comparison Method - This visual system is shown in the sketch of Figure 19B. It is used as a production control technique and is suitable for selecting standard, above standard or below standard devices in comparison with a reference reflector. The 100 ft. or more test distance is obtained by the use of mirrors, and the reflex illumination is obtained from a projection lantern equipped with an iris diaphragm to change the amount of light As long as the objective is only one of comparison this method is quite satisfactory. A small size of source and a long effective distance will favor devices with a narrow divergence pattern and will permit a rapid selection of reflectors on this basis. The uniformity of the illumination over the test area is very important.

3. Flicker Method - This system uses optical arrangement which alternately permits the observer to view the standard and the reflex reflector using the same retinal region for appraisal (see Fig. 19C). Judgment of the equality of reflector and standard is made by adjusting the standard until the flicker is eliminated. This system would seem to have considerable merit in reducing some of the variations in the visual technique, but will suffer from the limitations that all visual techniques are confronted with - variations in visual judgments of observers. The flicker method was proposed by Van Lear but has not been used for laboratory testing as far as the writer is aware.

Photoelectric -

4. Single Source Method - The general scheme for this photoelectric method of evaluation is shown in Figure 20A and in Reference 3. The important items to consider in this design are the size of the light source, the size of the reflex reflector, the test distance, the size of the receiver and the response characteristics of the photo cell and amplifier. It is believed that unless all parts of the system are reduced in scale by the same scale factor, the results may not be comparable at all divergence angles to tests made at greater distances under conditions representing field performance. Also unless the photo tube is used as a comparison device the spectral response of the photo tube may introduce appreciable errors.

5. Multiple Source Method - This photoelectric test setup is shown schematically in Figure 20B. The factors to consider here are the averaging effect of the entrance angles, divergence angles, and orientation angles due to the multiple sources, the size of the receiver, the size of the sources, the size of the reflector and test distances. For measurements on area reflecting materials the size of the reflex test plate is necessarily large and therefore may be very important. The test equipment is easy to use for measurements at fixed divergence angles and may be satisfactory for testing for specific performance requirements, but the system does not appear to be universal and the data obtained may not correlate with other laboratory findings. This does not infer that the results are invalid. They may be entirely acceptable for the required measurements.

6. Overall Efficiency Method - This photoelectric system is shown schematically in Figure 20C and Reference 4. It is basically a method of evaluating the overall return beam of a reflector. The design is based upon the interception of the total amount of flux within a divergence angle of approximately 0. 17 deg. to 1 deg. It is a method whereby large numbers of devices may be quickly evaluated for production control, but

cannot give a complete appraisal of field performance because of the lack of information on the divergence angle characteristics. It is possible for two different devices to have the same efficiency and still appear entirely different under roadway conditions.

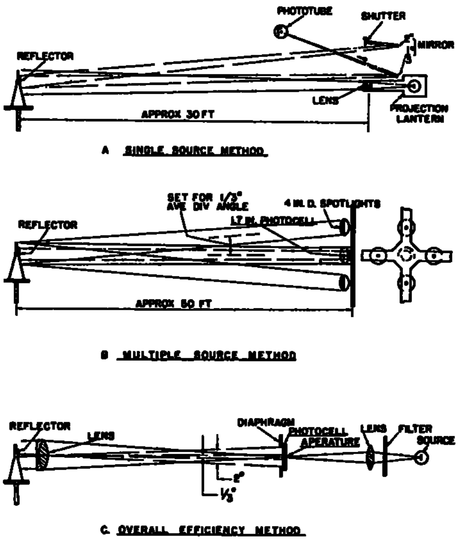


FIG. 20 PHOTOELECTRIC METHODS

CONCLUSIONS AND RECOMMENDATIONS

The test data that have been assembled and presented in this report will permit several general conclusions to be formulated:

1. The results of any test procedure should give an indication of the field performance of the device for the particular service for which it is intended. The service classifications that should be covered by performance specifications are: (a) Devices intended for long distance signaling. Units such as roadway delineators and truck flares would fall in this classification. (b) Devices for general service at intermediate distances constructed to the best standards. This service would include the reflex units used for trucks, commercial vehicles, trailers and for the marking of roadway obstacles. (c) General service units designed for intermediate distances but built to secondary standards. This classification would include the reflectors built into the lenses of passenger car rear lamps, supplementary reflectors on passenger cars, bicycles, and other miscellaneous installations. (d) Reflex devices used as signs, large area markers, or advertising media. This service requires wide acceptance angles (entrance angles) and wide return angles (divergence angles) for the light flux.

2. The visual data reported clearly indicate the need for a physical method of making the measurements. There is inherently too much scatter in the data of each observer and too large a variation among observers for the visual system to be practical for commercial use. The visual technique may be entirely satisfactory provided sufficient precautions are taken to insure standardized measuring conditions each time the technique is used. The proper use of the method entails making a large number of observations and examining the results statistically.

3. For a complete specification of a reflex reflector complete data on the distribution of the return flux should be available. The method of making the measurements should be completely described so that the validity of the results may be appraised. Preferably the data should be collected under conditions that have been standardized.

4. In order to insure the satisfactory performance of reflectors, sufficient specification points are required in the divergence angle measurements, entrance angle measurements and orientation positions to be certain that the reflector can meet the service for which it is intended. At the present time the two S. A. E. test points at divergence angles of 1/3 deg. and 2 deg. for one orientation, and several entrance angles are not sufficient to indicate field performance under service conditions.

5. A recommended test procedure based upon a physical photometric method has been developed. This procedure is included as Appendix B and should define the test conditions sufficiently to permit all types of reflex reflectors to be evaluated for any type of service.

6. Recommendations for specific intensities of various types of reflex

reflectors for the four different service classifications are being prepared and will be submitted for consideration in the near future. This will be a matter for joint action by all of the interested agencies and should be governed by the determination of minimum visibility requirements based upon other studies.

ACKNOWLEDGMENT

This material is the result of many hours of work and planning by the entire staff of the Testing Agency of the California Highway Patrol, the Institute of Transportation and Traffic Engineering, and by the engineers employed under University Research Grants and grants from the industry. Grateful acknowledgment is extended to these agencies. Particular credit is given to Messrs. A. P. Wagner, W. M. Heath, W. F. Dimmick, Basil Andrews, Lawrence Silva and J. T. Gier for their assistance in the collection of data and the development of equipment.

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APPENDIX A. INTERLABORATORY COMPARISON OF REFLEX REFLECTORS

A set of selected sample reflectors has been circulated among three of the principal laboratories that evaluate such devices for automotive service. This was done in order to determine the spread of values that might be expected due to the variations in laboratory procedures equipment and personnel. Specific inten sity measurements were made upon crysta and red plastic reflectors at 1/3° an 2° divergence angles. The results ar shown below.

Device	Divergence Angle	Laboratory Position	H-V	20°L-V	20°R-V	30°L-V	30°R-V	H-10°U	H-10°D
	Degree	SAE Spec	1.0	0.70	0.70	0.40	0.40	0.70	0.70
3 in.		No 1 Ave 18 readings	5.7	2.3	2.5	0.94	0.96	4.8	4.7
dia.red	1/3	No 2 Ave 3 ''	5.3	1.9			0.74	4.5	
plastic		No 3 Ave 3 ''	8.1	3.4	2.9	1.4	1.00	7.0	7.2
		No 1 Ave 18 ''	25.	11.	11.	4.4	4.9	20.	21.
3 in. dia.	1/3	No 2 Ave 3 ''	29.	10.			4.1	19.	
crystal plastic		No 3 Ave 3 ''	28.	12.	11.	5.6	5.0	25.	22.
		SAE Spec	0.05	0.05	0.05	0.03	0.03	0.05	0.05
3 in.		No 1 Ave 18 readings	0.12	0.06	0.06	0.04	0.04	0.08	0,08
dia.red	2	No 2 Ave 3 ''	0.30	0.13			0.08		0.20
plastic		No 3 Ave 3 ''	0.20	0.08	0.08	0.04	0.05	0.16	0.14
		No 1 Ave 18 readings	0.55	0.31	0.34	0.26	0.30	0.38	0.37
3 in. dia.	2	No 2 Ave 3 ''	1.1	0.60			0.57	0.77	
crystal plastic		No 3 Ave 3 ''	0.96	0.61	0.63	0.44	0.48	0.69	0.74

On two specific reflectors the following data were reported:

Reflector - 3 inch crystal plastic Stimsonite reflector
Entrance Angle - 0° (H-V)

Laboratory	Date	Divergence Angle			
		1/3 Degree		2 Degree	
		Refl. No. 10	Refl. No. 11	Refl. No. 10	Refl. No. 11
No 1 (visual)	7/14/48	30.	24.	0.52	0.62
No 2 (photoelectric)	8/25/48	31.	26.	0.89	0.99
No 1 (visual)	11/15/48	27.	28.	0.52	0.42
No 1 (visual)	12/30/48	24.	24.	0.45	0.62
No 3 (visual)	5/4/49	30.	30.	0.96	0.78
No 3 (photoelectric)	11/8/49	32.	26.	0.85	0.88

Values are specific intensity in candles/ft.c.

APPENDIX B. RECOMMENDED TESTING PROCEDURE

The following general ground rules are recommended as the basis for a standardized testing procedure for reflex reflectors.

1. Make all specific intensity and flux distribution measurements on uncolored (crystal) reflectors. The intensity measurements for colored devices should be determined from the spectral transmission data obtained from representative sample materials.

2. Use a reference comparison standard and reflector light source emitting white light at approximately 2360°K color temperature. This color temperature has been proposed for the reference source for all photometric measurements at photopic as well as scotopic levels. Measurements made using this reference standard will be valid and directly comparable with visual observations at all levels of illumination. The transmittance of filters should be computed using a reference source at 2360°K and the standard photopic visibility curve.

3. Use a photoelectric device to measure the light flux from the reflector. The receiver should approximate the conditions that exist during a visual appraisal insofar as the size of receiver area is concerned. This implies a maximum receiver aperture of approximately 10 millimeters diameter. The photoelectric device should be capable of giving a reliable indication for a source emitting 0.01 c.p. at a distance of at least 100ft. The arrangement of the photocell receiver should be such that it can be used to evaluate all divergence angles up to the maximum encountered in automotive service. Truck or bus operators may have their eye position as much as 85 in. away from the center of the off-side headlamp. This would represent a divergence of 4° at 100 ft. or 2° at 200 ft. It is suggested that the range of divergence angles should be limited to 0 - 2°. The photocell circuit should be reasonably stable and readily calibrated. A reference standard tungsten light at 2360°K should be available for checking the instrument at frequent intervals. The overall circuit should be reasonably linear. The spectral response should preferably approximate the visibility curve. This is not absolutely necessary if the comparison technique is used, however, the spectral response should be principally in the visible region in order to avoid spurious effects of infrared radiation.

4. The test distance should be at least 100 ft. If a shorter test distance is necessary the entire arrangement should be reduced to scale and should be based upon: (1) a 3 in. maximum dimension reflector, (2) a 7 in. maximum dimension light source, (3) a 10 millimeter maximum diameter receiver aperture.

5. Where the divergence angle characteristics are asymetric, measurements should be taken in at least 3 orientation angle planes. The recommended positions are 0°, 45° and 90°.

6. The minimum values of specific intensity at various divergence angles should be set up in terms of uncolored (crystal) reflex reflectors. The minimum intensity of colored reflectors should be specified as a percentage of the uncolored specifications; example, red - 10%, amber - 40%.

The method of measurement outlined will permit the divergence angle characteristics to be measured at all test points and under all conditions of illumination and observation and reflector positions that are required for any type of service. The values of specific intensity at the different divergence angles, entrance angles and orientation angles for each type of service will have to be decided by other visibility tests that are not a part of this investigation. This will be the subject of further research and discussion.

PHOTOMETRIC TESTS FOR REFLECTIVE MATERIALS

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SYNOPSIS

Photometric tests developed and now in use by the Michigan State Highway Department for reflectivity measurements and color determinations on reflex reflectors and diffuse reflecting materials are described. Detailed accounts of equipment and procedures used in both tests are accompanied by examples of data obtained and methods of computation.

Some fundamental physical concepts and the significance of measurements are discussed briefly, and several useful and interesting applications of the data are pointed out.

Included also are photographs illustrating the apparatus now in use by the Department.

The rapidly increasing number of applications of reflex reflecting materials to the field of highway engineering has stimulated a growing interest among road builders in the development of a sound yet practical test whereby the optical performance of these materials may be estimated.

Akin to knowledge of their optical performance, which usually refers to the ability of these materials to function adequately as reflectors under service conditions, there has arisen a growing awareness of the importance which the color of the reflected light is beginning to assume.

Recognizing the need for quantitative tests of reflectivity and color for this class of materials, the Michigan State Highway Department in July, 1948, initiated the development of such tests. A few months later the work assumed added importance because of the necessity of preparing specifications to cover reflective materials and signs of all types for a statewide Federal Aid re-signing program. Specifications incorporating these tests have been completed and in force for almost a year and have proved adequate thus far. Revisions will be made from time to time as the need for them arises.

It is with the hope of furthering the development and general adoption of uniform specifications governing the production, purchase and use of reflective materials that the present paper on the Michigan State Highway Department reflectivity and color tests is presented.

The paper contains a description of the equipment and procedures for the reflectivity and color tests. Examples of data and methods of computation are also included. The significance of optical measurements employed in both tests is discussed and some useful applications of the data are pointed out.

REFLECTIVITY TEST

The Michigan State Highway Department reflectivity test was developed for the purpose of measuring the reflectivities of all reflex reflecting materials normally coming within the scope of the Department. Such materials include plastic and glass reflector buttons, both colorless and colored; reflective sheet materials of all colors; prefabricated traffic marking signs; and laboratory specimens of beads on traffic marking paint, both white and yellow.

At the outset, several attempts were made at the Research Laboratory of the Department to secure satisfactory results by the use of relatively simple visual comparison methods. Optical wedges were tried out, and formulas were developed for their production and use. The Luckiesh-Moss extinction meter was studied in the hope that it might be adapted to the measurement of differences between reflectors. None of these attempts proved satisfactory.

Apparatus used by one manufacturer of reflector buttons for production control proved to be of value for subjective tests but obviously required the availability of a standard. Even when a standard was provided, however, no two operators agreed as to whether a sample was brighter or dimmer than the standard as the two approached each other in brightness, and if so, by how much.

Rotating disks of Polaroid were calibrated to extinction, yet no two people were in agreement as to when the same reflector was extinguished.

One well-known available commercial machine for testing reflector buttons was studied, but its use was vetoed on the ground that sufficient purity of divergence angles was not provided. As a last resort, the Department decided to assemble its own equipment.

Definitions of Terms and Significance of Measurements - "Reflex Reflector, Retroreflector, and Retrodirective Reflector" are all terms applied to reflective materials that have the property of returning light into the immediate neighborhood of its source regardless of the position of that source. To avoid confusion, a single term should be adopted in referring to this class of materials. In this paper the term "reflector" is used interchangeably with the longer forms.

TABLE 1

DELINEATOR ANGLES AND DISTANCES
For Passenger Car in Right-Hand Lane, Delineator on Right Shoulder

Car Distance, Ft	Sight Distance, Ft	Entrance Angle, Deg	Divergence Angle, Deg
12.5	21.1	53 67	4.74
25 0	30 2	34 22	3.32
50.0	52.8	18.78	1 90
75.0	77 0	12.78	1 31
100 0	101 8	9 65	0 99
150 0	151.0	6 47	0 67
200 0	200 7	4 86	0 50
300.0	300 4	3.25	0 34
400.0	400.2	2 43	0.25
500.0	500 1	1.95	0 20
600.0	600 0	1 62	0 17
700.0	700 0	1.39	0.14
800 0	800.0	1 22	0 13
900.0	900 0	1 08	0.11
1000 0	1000 0	0.97	0 10
1100.0	1100 0	0.89	0 09
1200.0	1200 0	0.81	0 08
1300.0	1300.0	0.75	0.08
1400.0	1400.0	0 70	0.07
1500.0	1500.0	0.65	0 07

"Specific Intensity" is the unit of reflectivity and is defined as the apparent candle power of the reflector, per foot-candle of illumination falling on it, per unit area of reflecting surface. In the case of cube-corner reflectors, unit area of reflector surface is the square inch. For sheet material, signs, and beads on paint, unit area is the square foot.

"Apparent Candle Power" of a reflector is its luminous intensity expressed as the equivalent intensity of a point source producing an equal illumination at the same distance. Mathematically, it is the product of the illumination, in foot-candles, returned by the reflector to the point of measurement, and the square of the distance from that point to the reflector, in feet.

"Angle of Incidence" or "Entrance Angle" is the angle between the direction at which light strikes the reflecting surface and a normal to the surface at that point. In locations where cube-corner reflectors are ordinarily used, the most important range of incidence angles is from 0 to 10 deg., which represents straightaway vehicle distances from the reflector all the way from infinity down to less than 100 ft. Entrance angles corresponding to various distances from car to reflector are listed in Table 1.

Reflectors of lower brightness than the cube-corner type are intended for use at shorter ranges of visibility and the optical characteristics of these and the so-called "wide-angle" sheet materials must be evaluated over a greater range of entrance angles.

"Divergence Angle" is the angle between the direction at which incident light strikes the reflecting surface and the direction from which the reflected light is seen or measured.

The pattern of the reflected light is a very important characteristic of reflex reflectors. High intensity of reflected light is achieved through the ability of the reflector to return the light incident upon it within a comparatively narrow cone around the axis of the incident beam. The greater the spread of the return beam, the shorter the effective perception distance becomes. For long range reflectors, most of the reflected light must be conserved within a cone whose half-angle (divergence angle) is not more than 1/3-deg. Assuming an average distance of 21 in. between the eye of the vehicle operator and his headlamps, a divergence angle of 1/3-deg. corresponds to a car distance of about 300 ft. Values of divergence angles for various car distances are also given in Table 1. Average heights of the driver's eyes above his headlamps for three different types of vehicle are shown in Table 2.

TABLE 2

HEIGHT OF DRIVER'S EYES ABOVE CENTERS OF HEADLAMPS

Type of Vehicle	Ave Height, Inches[a]
30 Passenger Cars	23.38
8 Busses	38 03
6 Trucks	37.00

[a]Based on average of 35 men and 21 women

Owing to the determinative nature of the divergence angle characteristic, any photometric test for the evaluation of reflex reflectors must be sufficiently selective with regard to divergence angle that measurements at different divergence angles may be made without excessive overlapping. In conformity with this requirement, the sum of the angles subtended by the light source aperture and receiving photocell face should not exceed 1/2-deg., and preferably should be kept under 1/3-deg. For the same reason, geometric limitations imposed by the dimensions of suitable light sources and photocells ordinarily available make it necessary in most cases to use a distance of at least 50 ft. between light source and reflector.

"Orientation Angle" is the angle, with reference to a given position, to which the reflecting surface is rotated about a central axis normal to that surface.

When measurements are made with a single photocell, reflectors of the cube-corner type exhibit more or less regular alternations of maximum and minimum intensity when rotated around their optical axes. In testing these materials, either the orientation of the reflector should be specified, or enough determinations should be made at random orientations to obtain a reasonably representative average. The latter method is preferable.

The optical performance of bead-reflectorized surface is not appreciably affected by variations in orientation.

Apparatus - Equipment for the reflectivity test, shown in Figures 1 through 4, consists of a goniometer for supporting the specimen, a bank of lights for illuminating it, and a photoelectric cell and accessories for measuring the light reflected. Incident light is measured by a separate foot-candle meter.

Angle of orientation is established by rotating the face of the goniometer about its horizontal axis (optical axis), and is capable of adjustment to any value up to 360 degrees. Provision is also made in the goniometer design for elevation and depression of the normal as much as 15 deg. above or below the optical axis of the light source.

As shown in the illustrations, the

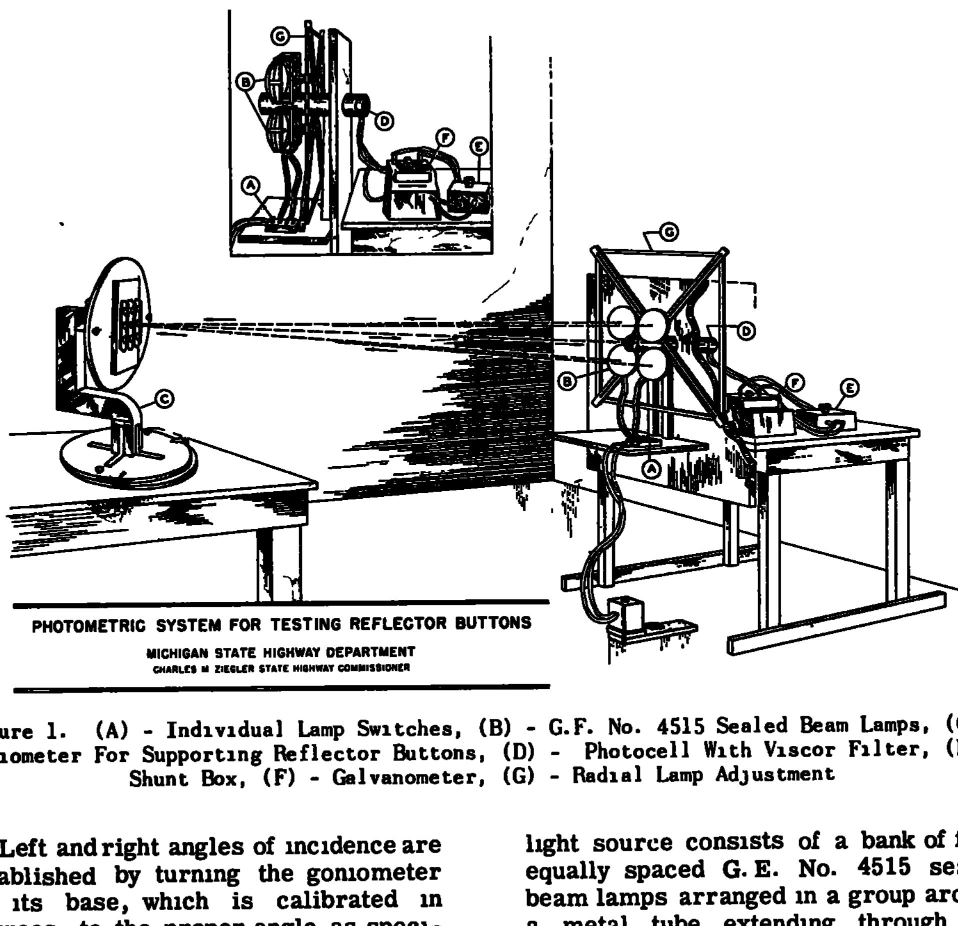


Figure 1. (A) - Individual Lamp Switches, (B) - G.F. No. 4515 Sealed Beam Lamps, (C) - Goniometer For Supporting Reflector Buttons, (D) - Photocell With Viscor Filter, (E) - Shunt Box, (F) - Galvanometer, (G) - Radial Lamp Adjustment

Left and right angles of incidence are established by turning the goniometer on its base, which is calibrated in degrees, to the proper angle as specified in the test procedure. For routine testing of reflector buttons, angles of 0, 10, 20, and 30 deg. are commonly used. In cases where wide-angle sheet materials are being tested it is necessary to include, in addition to these, angles of 40 and 50 deg. For reflectorized traffic marking paints, very large angles of incidence are desirable, as these are utilized in actual practice.

light source consists of a bank of four equally spaced G. E. No. 4515 sealed beam lamps arranged in a group around a metal tube extending through the center of the cluster. Each lamp is supported in such a manner that it may be turned in any direction, as well as displaced laterally toward or away from the axis of the metal tube. Angle of divergence is controlled by radial displacement of the lamps from the tube.

Routine testing in Michigan requires an angle of divergence of 1/3-deg., which is attained by establishing a radical distance of 3-1/2-in. between the center of the tube and the center of each lamp, the distance from the reflecting surface to the surface of the receptor photocell being exactly 50 ft.

The receptor photocell is clamped tightly against the rear end of the metal tube. The cell is a Weston Photronic Cell (barrier layer type), Model 594RR, equipped with a Weston Viscor filter, and is thus chromatically corrected to have a spectral response comparable to that of the average human eye. It has a current output of approximately 1.75 microamperes per foot-candle of incident light with the visual correction filter in place.

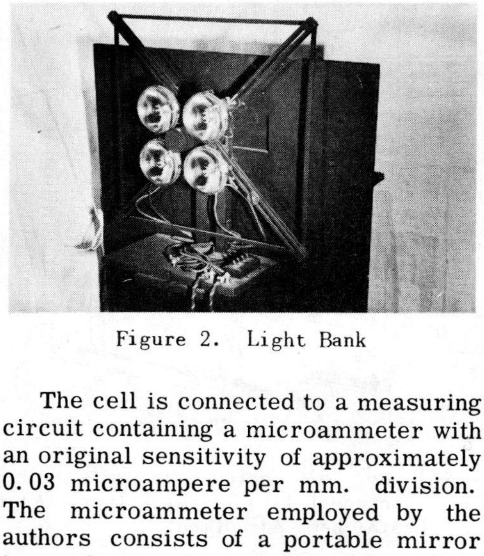


Figure 2. Light Bank

The cell is connected to a measuring circuit containing a microammeter with an original sensitivity of approximately 0.03 microampere per mm. division. The microammeter employed by the authors consists of a portable mirror type galvanometer purchased from G-M Laboratories, Chicago, catalog number 570-402. A suitable shunt system is included in the circuit to increase the range of the instrument by steps of approximately 10 to 1 and 50 to 1. The shunt used in this assembly was built in the Michigan State Highway Department Research Laboratory.

Incident light on the reflector being tested is measured with the aid of a Weston Foot-Candle Meter, Model 614, containing a duplicate of the receptor photocell, also visually corrected.

Lamps have individual switches, and a master control is provided by a Square D, Class 9002, Type FB6 foot switch. A voltage regulator in the lamp circuit is desirable but, except under unusual conditions, is not essential.

Procedure - Requirements for placing the apparatus for routine testing necessitate establishing a distance of 50 ft. between the receptor photocell and the reflecting surface. Extraneous light

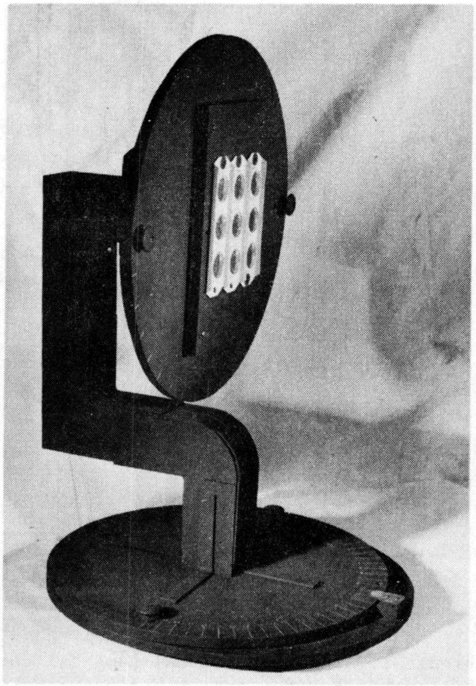


Figure 3. Goniometer

should be kept at a minimum, although the light in a normally dim corridor has no effect upon the accuracy of the results. It is of distinct advantage to hang a black drop cloth behind the goniometer.

Considerable care should be exercised in the collimation of the apparatus, and the alignment should be checked at the beginning of each test. The 50-ft. distance should be measured exactly. The specified divergence angle should be checked after adjustment of the lamps.

The sample is mounted on the goniometer in such a manner that its center is opposite the center of the goniometer face and its optical axis normal to that face. For precise collimation, the entrance angle of the goniometer should be set at 0 deg. and the sample replaced by a specular mirror. Adjustment of the goniometer may then be carried out until the operator, sighting through the metal tube in the center of the multiple light source, sees the reflected image of his eye in the mirror.

The lamps are turned on and individually adjusted so that the sample is illuminated uniformly, the 3-1/2-in. lateral displacement of each lamp being finally checked after uniform illumination of the sample has been achieved. Uniformity of illumination is considered satisfactory when the incident light as measured at five points by the foot-candle meter varies by no more than ± 5 percent from the average value. The average illumination in foot-candles is recorded as total incident light.

From the total incident light must be subtracted the ambient incident light, which is the illumination from the room falling on the sample. The latter illumination is so small (usually about 1 foot-candle) that its contribution in terms of reflex reflection along the optical axis is minute, and is quite beyond the sensitivity of the galvanometer to evaluate. The ambient light is diffuse, not unidirectional, and this diffuse light is added by the photocell to the unidirectional light from the artificial source, so that it is significant in the record of the incident light and should be subtracted. The difference between the total incident light and the ambient incident light is recorded as the incident light.

A black mask coated with dull optical black is next placed in front of the reflecting surface with the lamps turned on, and the reflected light measured by the receptor photocell. This value, which includes stray light entering the tube from other sources, is also very small, usually about 0.02 f.c., and is recorded as the basic reflected light. The mask is removed from the face of the sample and another reading taken, this being recorded as the total reflected light. The basic reflected light is subtracted from the total reflected light and the difference is recorded as the reflected light at each setting of the goniometer.

In testing reflector buttons having reflecting surfaces less than 6 sq. in. in area it is frequently desirable to group two or more buttons about the center of the goniometer face in order to provide sufficient reflecting surface area for adequate galvanometer response.

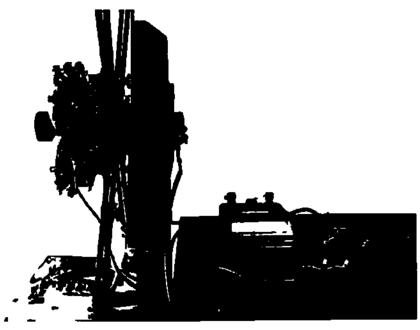


Figure 4. Light Measuring Equipment

Essentially the same procedure is carried out in determining the specific intensities of reflectorized sheet materials. With these materials, however, considerably larger areas are required in order to produce adequate galvanometer deflections. A black mask having a central circular cut-out of 2 sq. ft. area is fastened over the sample of sheet material and the latter centered on the goniometer as in the case of reflector buttons.

Traffic marking signs may be given the same treatment as that of reflectorized sheet materials, either with or without use of the circular cut-out mask. Care must be taken, however, to mask out portions of signs the reflective characteristics of which differ from those of portions under study.

Reflectorized paint is usually applied to 6-by 18-in. laboratory panels in stripes 4 in. in width. Any convenient reflecting area of these may be masked out for measurement on the goniometer, although as many as three complete panels have at times been required.

Practical Considerations - The reflectivity test requires one operator and one assistant. The assistant adjusts the angles of the goniometer as directed by the operator and manipulates the optically black mask. The time required for average routine testing varies from 10 to 15 min., depending upon the number of collimating adjustments necessary. Computations require about 10 min.

cells used in this test are larger than those of the human eye, sufficient purity of divergence angle is available to satisfy essential engineering requirements within practical limits. The larger photocell apertures are compensated for to some extent by the fact that the aperture of the light source is substantially less than that of the conventional automobile headlamp.

Electronic photocells of very small aperture and high sensitivity are available on the market, but their use does not seem warranted in quality control

TABLE 3

COMPUTATION OF SPECIFIC INTENSITY

Distance, Photocell to Reflector 50 ft
Divergence Angle: 1/3 degree

Entrance Angle, Deg	Galvanometer Reading[a] Basic	Total	Net (Mean, L. & R.)	Illumination Returned, F C	App. C P	Specific Intensity,[b] C P per F C per sq in
0	1.4	86.0	84.6	1.85	4625	7.0
10 L	1.4	77.2				
10 R	1.4	71.7	73 1	1.59	3975	6.0
20 L	1 4	35.0				
20 R	1.4	34.8	33.5	0.73	1825	2 8
30 L	1.4	17.0				
30 R	1.4	17.9	16 1	0.35	875	1.3

[a]Shunt box setting 45.85 scale divisions per foot-candle
[b]Incident light 108.2-1 4 106.8 F C. , Area 6.204 sq. in

Reproducibility of results is within ± 3 percent, even without the use of a constant-voltage regulator, but this presupposes a periodic check on the calibration of the foot-candle meter and receptor photocell. (These calibrations are easily checked by the use of secondary standards and do not involve return of instruments to the manufacturer.) This degree of precision compares favorably with the guaranteed accuracy of most commonly available electrical measuring instruments on the American market, and is well within the requirements for accuracy of any State highway department. Total cost of the entire equipment is moderate.

Although the apertures of the photo-

testing at this time. Electronic cells cannot be color-corrected as easily or as accurately as the barrier layer type of cell. Moreover, their electrical response is much weaker and must be amplified by costly additional apparatus. The greater purity of divergence angle obtainable does not seem to be of great practical significance in view of the relatively large range of angles represented by differences in vehicle types and individual driver heights.

On the credit side, their use might prove valuable in further fundamental research and would make possible shorter distances between reflector and light source in photometric tests.

Test Results and Applications - Specimen results from a reflector test are given in Table 3 to illustrate the mathematical treatment of the data. Net galvanometer readings (column 4) are first converted to equivalent illumination in foot-candles (column 5). Reflected light in foot-candles is converted to apparent candle power of the reflector (column 6) by multiplying by 2500 (square of the distance, 50 ft.). This is simply an application of the inverse square law. Final values for specific intensity (column 7) are then computed by dividing the apparent candle power by the incident light in foot-candles, and again by the area of the reflecting surface.

The three-dimensional graphs of Figures 5, 6, and 7 are presented to show how the data from the photometric tests of different makes and types of reflectors may be used effectively for the purpose of comparison. From the graphs, figures were obtained which made it possible to predict, in the laboratory, the field performance of the reflectors whose characteristics are shown. These reflectors were then put into use on the highway and their performance was found to be exactly as predicted.

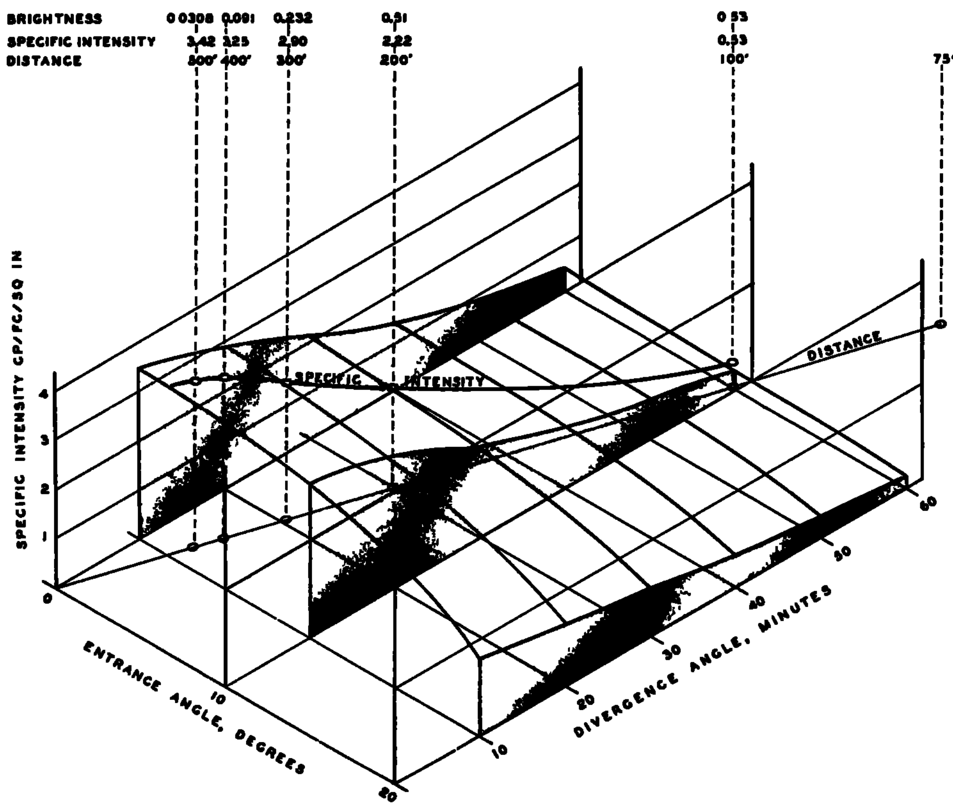


Figure 5. Three Dimensional Diagram of Specific Intensity vs. Entrance and Divergence Angle Button "E"

Similar checks of field performance against laboratory tests have been observed repeatedly in the case of reflectorized sheet materials, traffic marking signs, reflectorized paints and railroad crossing markers.

By means of the data on automobile headlamp illumination shown in Figure 8, the test results for the two delineators of Figures 5 and 6 were extended further to indicate the true brightnesses of the reflectors as they are approached by a vehicle. The curves of Figure 9 are a graphic illustration of important differences in reflector characteristics.

Reflectivities of various types of bead-reflectorized materials are given in Figure 10 and 11. None of these materials approaches the cube-corner type of reflector in brightness but each finds an appropriate application in highway signing and marking.

and similar diffuse reflecting materials normally coming within the scope of the Department.

Equipment and test procedure are based on the pioneer work of Professor Arthur C. Hardy of the Massachusetts Institute of Technology and follow in general the requirements set forth in "Standard Method of Test for Spectral Characteristics and Color of Objects and Materials", ASTM Designation: D307-44.

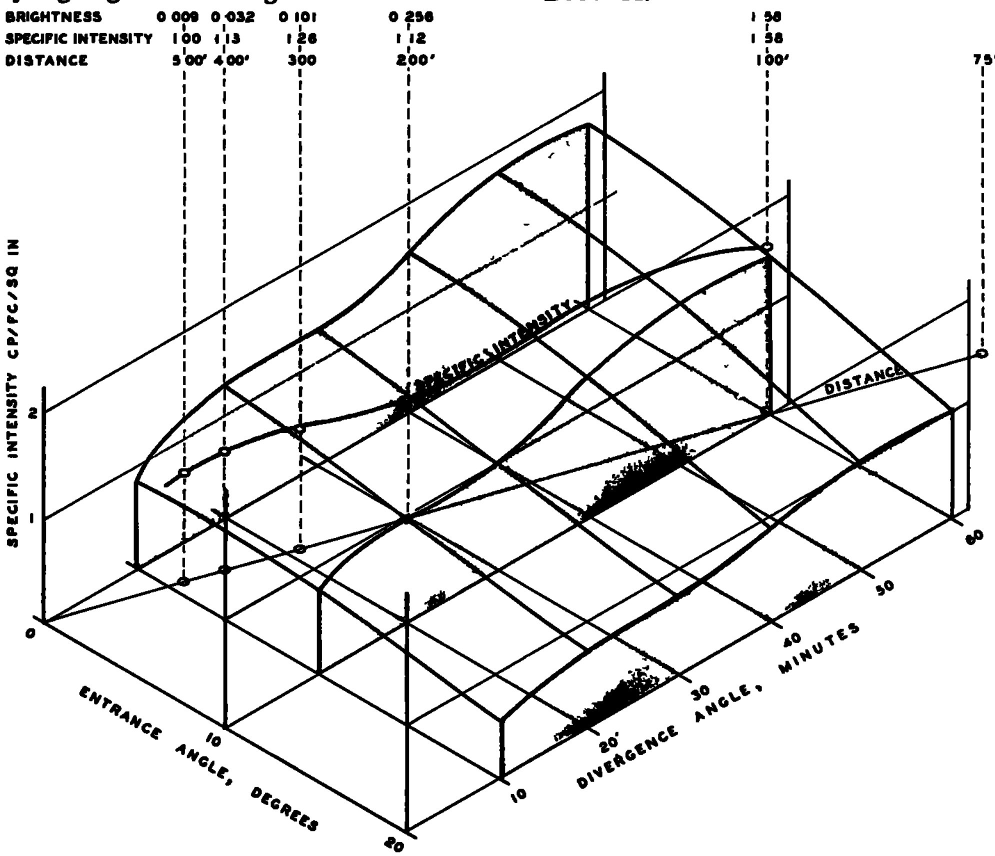


Figure 6. Three Dimensional Diagram of Specific Intensity vs. Entrance and Divergence Angle Button "F"

COLOR TEST

The Michigan State Highway Department color test was adopted to satisfy a growing need for a means of identifying the hues of colored reflector buttons, and has been adapted to the evaluation of the reflected colors of all reflex reflecting materials and of the spectral apparent reflectances of traffic paints

Apparatus - Equipment for the color test shown in Figures 12, 13 and 14 is built around the major piece of apparatus, a Central Scientific Company Cenco-Sheard Spectrophotelometer, catalog No. 12315, and accessories. The spectrophotometer contains a barrier layer photocell, which actuates a G. E. No. 32C245G13 galvanometer having a sensitivity between 1.2 and 1.5 by 10^{-9}

ampere per mm. division. For purposes of stability, the galvanometer is mounted upon a 65-lb. block of concrete. Although the spectrophotometer is a rather expensive instrument, it is a versatile one that has many other useful applications in the laboratory.

positioning (a) the sample, (b) the standard and (c) a dull optically black surface in front of the entrance slit of the spectrophotometer.

Distance from reflecting surface to entrance slit is maintained at approximately 52 in. for maximum galvanom-

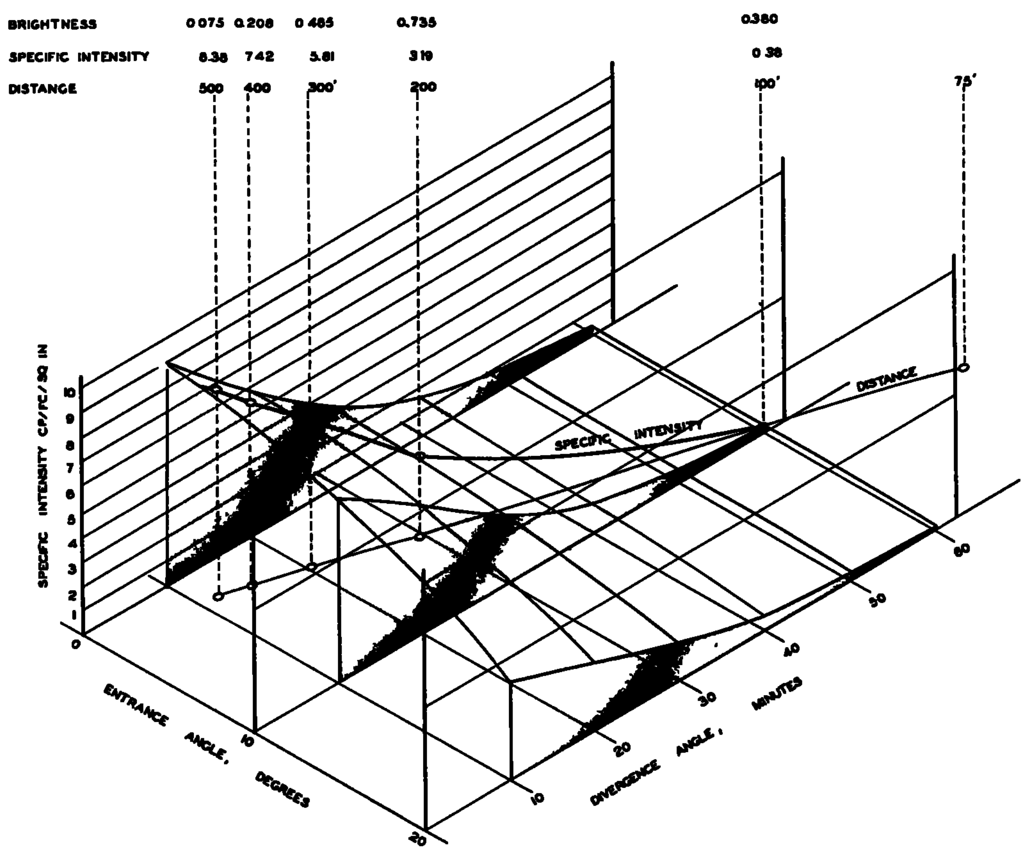


Figure 7. Three Dimensional Diagram of Specific Intensity vs. Entrance and Divergence Angle Oval Sign Button "D"

The light source is a single G. E. No. 4560 sealed beam lamp (airplane landing type) operating at 28 volts and requiring 600 watts for peak operation. A maximum intensity of 600,000 candle power is produced at beam center. The lamp is operated on the 110-volt line in series with a bank of 7 cone-shaped heating coils, the coils themselves being in parallel.

A rotatable target is provided as shown in the illustration for alternately

eter response. A 2-in. inside diameter cardboard tube 20 in. in length, painted inside and out with dull optical black, is held tightly against the entrance slit and pointed directly at the reflecting surface. Collimation is so adjusted that the entrance slit and reflecting surface are at the same elevation, and the optical axis is normal to both.

For the testing of reflex reflectors, the lamp is placed at a point in front of the target, above and behind the spectrophotometer, with a distance of 7 ft. between the reflecting surface and the lens of the lamp, and the angle between the optical axis of the entrance slit and that of the lamp (angle of divergence) is kept as small as geometrical considerations allow. With distances less than 7 ft., heat from the lamp becomes objectionable.

For the testing of diffuse reflectors, specular gloss is eliminated by adjusting the incidence angle to approximately 45 deg.

TABLE 4

COLOR TEST DATA AND COMPUTATIONS

Wave length, millimicrons	Crystal + Black	Amber + Black	Black	Crystal	Amber	Reflectivity Factor, R_λ	Ibid Corrected at 660 mu	Specification
400	0.38	0.14	0.07	0.31	0.07	0 226	0 146	0.05 - 0.20
20	0.50	0 18	0.08	0.42	0.10	0 238	0 154	0.05 - 0.20
40	1.25	0.48	0 18	1 07	0.30	0.280	0.181	0.05 - 0.20
60	1.81	0.53	0.25	1 56	0.28	0 179	0 116	0.06 - 0 20
80	2.40	0.72	0.33	2.07	0.39	0.188	0.122	0.07 - 0.20
500	3.15	0 95	0.40	2 75	0.55	0.200	0.129	0.08 - 0.20
20	3.65	1.00	0.42	3.23	0.58	0.180	0.116	0.09 - 0.20
40	4.07	1.30	0.50	3.57	0.80	0 224	0.145	0.12 - 0.20
60	5.02	2 97	0.50	4.52	2.47	0 546	0 353	0.30 - 0.50
80	5.30	5 09	0 53	4.77	4.56	0 956	0.619	0.55 - 0.75
600	5 00	6.10	0 52	4.48	5.58	1 245	0 805	0.75 - 0.85
20	4.60	6 10	0.52	4 08	5.58	1.365	0.883	0 86 - 0.91
40	3 52	4.80	0.52	3 00	4.28	1.428	0.923	0.89 - 0.94
60	2 47	3.32	0 50	1 97	2 82	1.430	0 925	0.90 - 0.95
80	1.50	2 00	0.49	1 01	1 51	1 495	0.967	0.90 - 0.95
700	0 93	1.01	0.49	0.44	0.52	1 181	0.765	0.92 - 0.97

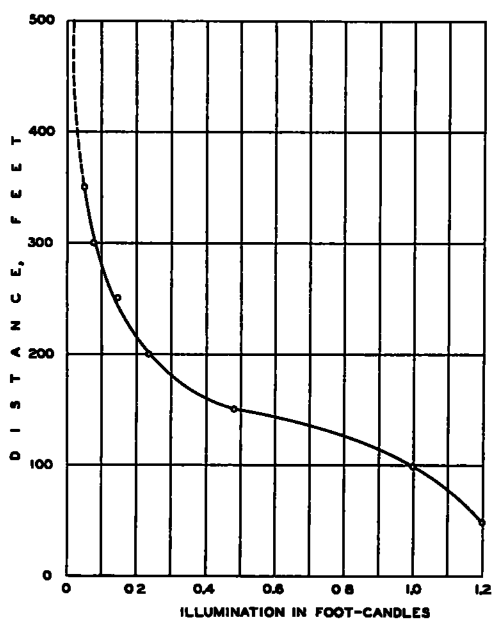


Figure 8. Illumination of Road by 1938 Car, Multibeam Headlamps (At Point Six Feet To Right of Car)

Procedure for Reflex Reflectors - In the case of reflex reflectors the standard employed is a crystal (colorless) reflector of the same size, shape, configuration and composition as those of the colored sample, the only difference between standard and sample being one of color. Differences in specific intensity are automatically compensated for in the method of computing results.

Sample and standard are placed in their respective positions on the target. The entrance slit of the spectrophotometer is adjusted to 2.5 mm. and the exit slit to a nominal 20-millimicron width.

The spectrophotometer is set to a wavelength of 400 millimicrons, the lamp is turned on, the standard is swung into the optical axis and a reading is taken. The sample is next rotated into position and its reading recorded. The blank value is found by

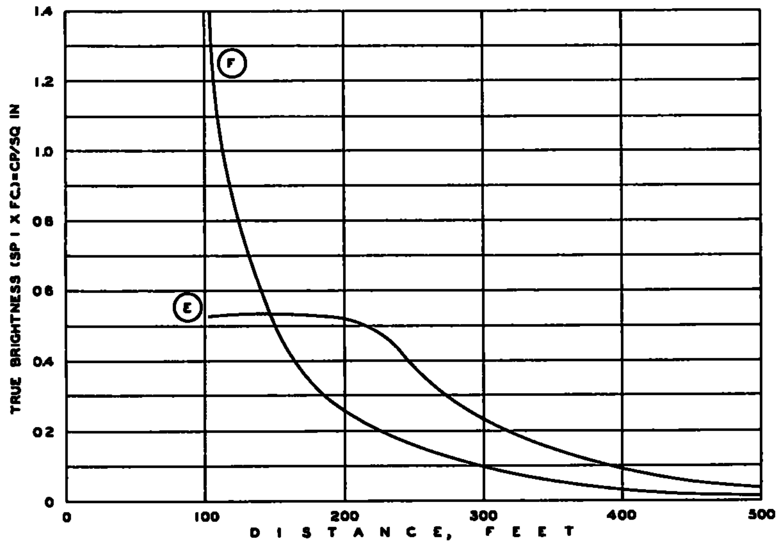


Figure 9. True Brightness of Delineators vs. Distance from Car (Apparent Candlepower per sq. in.)

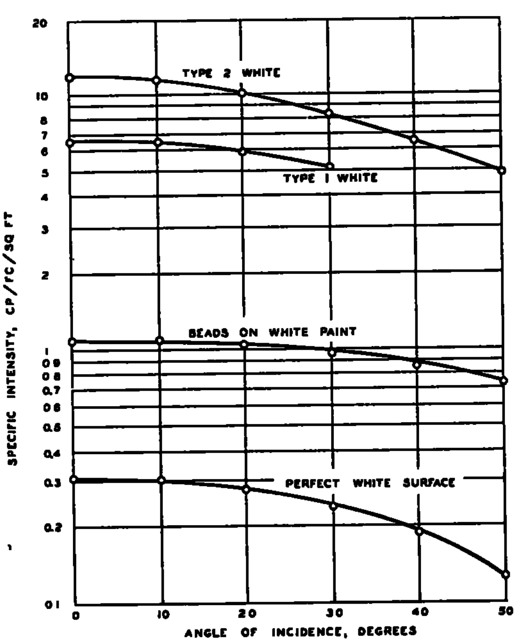


Figure 10. Reflective Properties of Bead-Reflectorized Surfaces

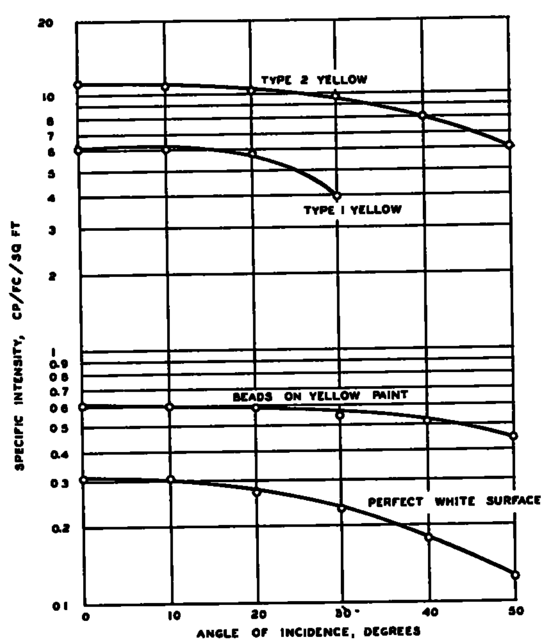
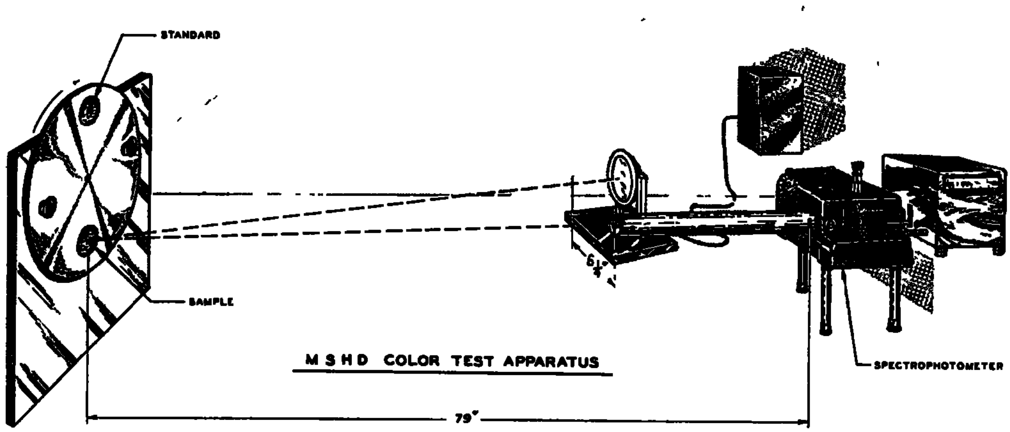
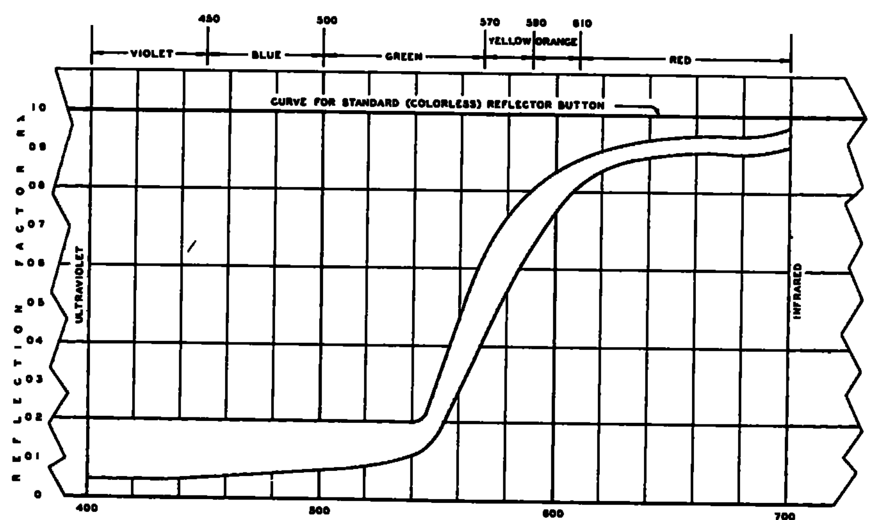


Figure 11. Reflective Properties of Bead-Reflectorized Surfaces

swinging any black portion of the target into position and taking the "black" reading. These readings are repeated at wavelength increments of 20 millimicrons throughout the visible spectrum up to and including a wavelength of 700 millimicrons. In the absence of a constant-voltage transformer it is essential to check the readings taken at the same wavelength until the operator is certain that no significant voltage fluctuations have occurred during the time the three readings were recorded at that wavelength.



M S H D COLOR TEST APPARATUS



SPECTRAL APPARENT REFLECTIVITY
ICI ILLUMINANT 'A'
COLORED PLASTIC REFLECTOR BUTTON
(AMBER)

Figure 12.

Computations - Data from an actual color test are shown in Table 4. The basic "black" reading is subtracted from the crystal and colored readings at each wavelength. The resulting reading for the sample is divided by that for the standard at the same wavelength, and the ratio, R_λ, is recorded as the spectral apparent reflectivity of the sample for each wavelength included in the determination.

Spectral apparent reflectivities are plotted against wavelength, as in the ASTM procedure. As a rule, however, these values have to be corrected for differences in specific intensity between sample and standard. In the case of amber plastic reflector buttons, it is Michigan State Highway Department practice to determine the factor required to convert R_λ at 660 millimicrons to the value, 0.925. All values of R_λ are then multiplied by the same factor, and the corrected values of R_λ are plotted against wavelength. It is found that this method works very well in avoiding elevation or depression of "amber" curves, and there is no reason why similar adjustments are not possible in the case of any other color.

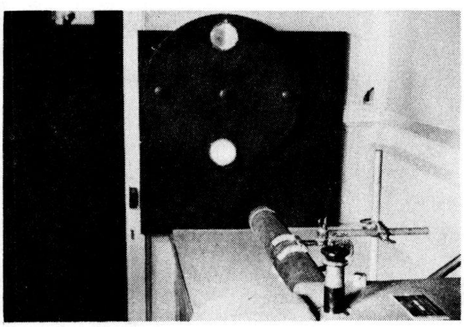


Figure 13. Target

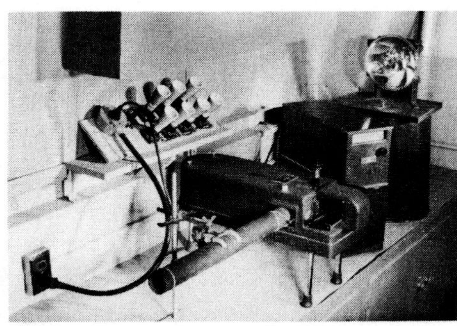


Figure 14. Spectrophotometric Assembly

Applications - With the help of the color test, the Department has succeeded in establishing appropriate specifications for the color of amber plastic reflector buttons. Similar specifications for reflectors of other colors will doubtless be forthcoming when and if reflectors of other colors are brought into use by the Department.

Once a color curve has been established, it is possible to identify that color objectively at any time thereafter and to follow with precision the extent or absence of fading, darkening, or of any other alternation of the color without recourse to visual comparison with color chips or with a so-called master color standard. A color curve obtained by this test is definite and reproducible, and constitutes a permanent record.

Procedure for Diffuse Reflectors - In the case of diffuse reflectors, of which traffic paints are examples, the same procedure is followed except that a disk coated with freshly deposited magnesium oxide is used as the standard white, and the sample is sprayed on a similar disk of the same diameter. The light source is placed at the same distance, but at an entrance angle of 45 deg. to eliminate specular gloss.

Computations follow the ASTM procedure for calculating the luminous apparent reflectance, R_S, in percent.

Time and Personnel Required - A single operator handles all Department tests involving work with the spectrophotometer. Color tests on reflector buttons require 45 min. for the determinations and 30 to 45 min. for computing and plotting the curve. Determination of R_S for traffic paints and similar materials requires 1 hr. for the test and 1 hr. for the calculations. As many as four determinations on diffuse reflecting materials are frequently completed in a single day This includes the time required for all calculations and for four separate depositions of magnesium oxide

CONCLUDING STATEMENT

The reflectivity and color tests just described have been proved over a period of more than a year to satisfactorily fulfill essential requirements so far established by the Department The simplicity, availability, and reasonable cost of the equipment employed recommend it for use in quality control by both producer and consumer Ease of assembly and operation are additional advantages, any laboratory technician of ordinary ability can perform the tests

Refinements of equipment and procedures, and extension of the applications of photometric tests are bound to come In the meantime, the Michigan tests should serve a useful purpose in the highway industry as a first step toward the effective evaluation of reflective materials

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